MAY 2010

SACRAMENTO REGIONAL COUNTY SANITATION DISTRICT

Low Dissolved Oxygen Prevention Assessment

prepared by

LARRY WALKER ASSOCIATES

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMMARY

Sacramento Regional Wastewater Treatment Plant (SRWTP) provides regional treatment of sewage generated in the greater Sacramento metropolitan area. The treated effluent is discharged to the Sacramento River at Freeport. The effluent contains residual compounds that may be oxidized in the river through respiration by organisms in the river consuming oxygen from the water column. The Basin Plan contains objectives for dissolved oxygen applicable to the Sacramento River downstream of the SRWTP point of discharge. The analysis presented herein is used to determine the allowable loading of oxygen demanding substances in the SRWTP effluent that will ensure compliance with the dissolved oxygen Basin Plan objective.

To assist in the analysis of the SRWTP discharge and evaluation of the separate carbonaceous and nitrogenous affects on dissolved oxygen, the classic Streeter-Phelps equation was expanded to include oxygen depletion of carbonaceous oxygen demanding compounds and ammonia present in the water column. Additionally, the decay of organic nitrogen into ammonia is included in the expanded Streeter-Phelps model. The low dissolved oxygen prevention assessment (LDOPA) model calculates daily averaged dissolved oxygen in the Sacramento River from the discharge at Freeport to the confluence of the Sacramento and San Joaquin Rivers. The model uses river flow rate and temperatures input data developed for the SRCSD DYNTOX model (SRCSD 2009) providing a 70-year period of record as a basis for the model simulations.

Because the dissolved oxygen objective is being evaluated in the river downstream of the discharge, the total oxygen demand, or ultimate oxygen demand (UOD), of the SRWTP effluent is the proper parameter to control to ensure compliance with the Basin Plan objective. Scenarios were evaluated in the LDOPA model, where various loads of UOD were input and the downstream compliance in the river with the Basin Plan objective was evaluated. The effluent flow rate was evaluated at 181 and 218 mgd. The LDOPA model was constructed to incorporate the variability of input parameters by using the river flow rate and temperatures in continuous simulation, and calculating other inputs from their representative statistical distributions in a Monte Carlo manner. A model run incorporates many repeated loops of the 70-year period of record to calculate the statistical distribution of dissolved oxygen at locations downstream of the discharge for each day in the period of record. As a conservative measure, compliance with the Basin Plan objective is assessed as the minimum modeled dissolved oxygen to be at least 7.0 mg/L with a 95% confidence level. For example, in the 218 mgd scenario, the modeled minimum dissolved oxygen is 7.3 mg/L occurring just upstream of Rio Vista with at least 7.0 mg/L at a 95% confidence level occurring between Rio Vista and Emmaton (see **Figure 14**).

The LDOPA model is used to demonstrate the strong seasonality of the dissolved oxygen in the Sacramento River. Generally, when water temperatures are cooler the dissolved oxygen concentrations are higher, and as river flow rates increase there is less change in dissolved oxygen for a given effluent condition. Due to the strong seasonality of the dissolved oxygen, the LDOPA model was run using current UOD effluent concentrations for the months of November through April, the Wet Season, and any reductions from current performance were only applied May through October, the Dry Season. For the Wet Season, at a 218 mgd effluent flow rate and current levels of UOD, the minimum modeled downstream dissolved oxygen concentration is slightly greater than 7.0 mg/L at the 95% confidence level.

When considering strategies to control oxygen demanding substances in the SRWTP effluent, a UOD load limit would allow all management options available to the SRCSD, as opposed to concentration based limits, which would trigger modification based on effluent flow rate or control strategy. For example, increasing water reuse in the dry season would lower the volume of treated discharge, allowing greater concentrations in the effluent, however the allowable loading levels would remain unchanged. Additionally, as UOD load limits would be implemented to ensure compliance with the dissolved oxygen Basin Plan objective, there should be limitations based on the secondary treatment standards for BOD_5 concentrations and ammonia water quality based effluent limitations for the protection of aquatic life. Proposed effluent limitations on UOD loading generated from the LDOPA model results are summarized in **Table 1**. The proposed seasonal limitations are determined to ensure the minimum dissolved oxygen would be at least 7.0 mg/L with a 95% confidence level over the range of hydrologic conditions that have been observed over a 70-year period. Concentration based effluent limitations for BOD_5 and proposed ammonia are presented in Table 2. Effluent limitations for BOD_5 are based on existing secondary treatment technology limits. Proposed ammonia water quality based effluent limits reflect compliance based on an acute mixing zone of 60 feet and a chronic mixing zone of 350 feet as evaluated using the DYNTOX dynamic model assessments performed by the District (SRCSD 2009). The combination of a UOD loading limitation and the existing BOD limits with proposed water quality based effluent limitations for ammonia will provide the district flexibility in implementing control strategies to meet the Basin Plan objective for dissolved oxygen

Table 1: Proposed Effluent UOD Loading Limitations for the Protection of Basin Plan objectives for Dissolved Oxygen.

	Dry Season UOD[(1)] (lbs/day)		Wet Season UOD[(1,2)] (lbs/day)	
Q_{eff}	AMEL	MDEL	AMEL	MDEL
181	192,000	234,000	307,000	438,000
218	192,000	234,000	376,000	537,000

(1) Ultimate Oxygen Demand = 8.34*[1.5*(BOD_5) + 4.6*(Ammonia)]*Q_{eff} ; BOD_5 in mg/L, ammonia in mg/L as N, and Q_{eff} in mgd.
(2) Wet Season UOD set to Current Performance

Table 2: Proposed Concentration Based Effluent Limitations for BOD_5 and Ammonia.

Parameter	Units	Effluent Limitations: Average Monthly	Average Weekly	Maximum Daily
BOD_5	mg/L	30	45	60
Ammonia[(1)]	mg/L as N	37	---	47

(1) Based on acute mixing zone of 60 feet and chronic mixing zone of 350 feet as evaluated with DYNTOX dynamic model.

INTRODUCTION

Sacramento Regional Wastewater Treatment Plant (SRWTP) discharges treated effluent to the Sacramento River at Freeport. A map of the Sacramento River – San Joaquin River Delta (Delta) is presented in Figure 1 including the point of discharge. The Water Quality Control Plan for the California Regional Water Quality Control Board Central Valley Region, Fourth Edition (Basin Plan)[1] contains an objective for dissolved oxygen that applies to the portion of the Sacramento River that is within the legal boundaries of the Delta. The Sacramento Regional County Sanitation District (SRCSD or District) has evaluated whether future operations of the SRWTP will have the potential to result in excursions of the applicable Basin Plan objective for dissolved oxygen in waters downstream of the discharge. A discussion of the analysis and recommendations are presented herein.

Oxygen in the water column is necessary to maintain healthy populations of desired aquatic life, with fish generally requiring higher minimum dissolved oxygen levels than other aquatic life. In general, oxygen demanding substances (e.g. carbon and nitrogen compounds) present in receiving waters are oxidized by microorganisms (bacteria and algae) resulting in the consumption of oxygen from the water column. The water column is reaerated as oxygen in the atmosphere is transferred across the water surface. If sufficient quantities of oxygen demanding substances are present in the water column, the rate of oxygen consumption may be greater than the reaeration of oxygen from the atmosphere causing dissolved oxygen levels to drop in the water column thereby potentially creating a low dissolved oxygen condition. As oxygen demanding compounds are oxidized and their concentrations are reduced, the rate of oxygen consumption falls and the reaeration acts to increase dissolved oxygen levels in the water column. The typical response of dissolved oxygen downstream from a discharge containing oxygen-demanding substances, like effluent from the SRWTP, is to first decrease and then increase some distance downstream, forming a characteristic sag curve. Increasing the volume of treated effluent discharged to the Sacramento River may result in an increased loading of oxygen demanding substances to the river, and potentially result in a deeper oxygen sag curve. A measure of the oxygen demanding substances in a volume of water is the ultimate oxygen demand (UOD) that corresponds to the total amount of oxygen required to completely oxidize the constituents in the water. To protect the beneficial use and ensure compliance with the Basin Plan objective for dissolved oxygen downstream of the discharge, the following is an assessment of SRWTP operating conditions, Sacramento River conditions, and measures that could be implemented.

The assessment begins with a review of the applicable Basin Plan water objective for dissolved oxygen, and other water quality criteria for dissolved oxygen. Next, a Streeter-Phelps type model developed to assess dissolved oxygen downstream of the SRWTP discharge is discussed. Details of the model development are provided in Appendix A. The model is used to determine the UOD load necessary to attain the Basin Plan objective for dissolved oxygen given receiving water conditions likely to occur based on a 70-year period of record. The model domain encompasses approximately 46 river miles of the Sacramento River from the point of SRWTP discharge at Freeport to the confluence of the Sacramento and San Joaquin Rivers as indicated as the dark blue shading on Figure 1. Further, the assessment identifies various management

[1] (http://www.swrcb.ca.gov/rwqcb5/water_issues/basin_plans/)

options of the SRWTP that could be pursued to prevent low dissolved oxygen levels downstream of the SRWTP discharge to maintain compliance with the applicable Basin Plan objective. For example, the SRWTP has initiated process optimization to reduce ammonia concentrations in the effluent in an effort to reduce the UOD load discharged to the Sacramento River. The SRCSD intends to further evaluate reducing oxygen demanding substances through process optimization, and as necessary, develop additional alternatives to reduce UOD including consideration of internal return flow treatment, expansion of the District's water recycling program, or additional treatment of a portion of the SRWTP effluent flow.

BASIN PLAN OBJECTIVE

The Basin Plan contains a numeric water quality objective for dissolved oxygen as follows:

> Within the legal boundaries of the Delta, the dissolved oxygen concentration shall not be reduced below:
>
> 7.0 mg/l in the Sacramento River (below the I Street Bridge) and in all Delta waters west of the Antioch Bridge; 6.0 mg/l in the San Joaquin River (between Turner Cut and Stockton, 1 September through 30 November); and 5.0 mg/l in all other Delta waters except for those bodies of water which are constructed for special purposes and from which fish have been excluded or where the fishery is not important as a beneficial use.

The Basin Plan objective of 7.0 mg/L dissolved oxygen is the applicable numeric water quality objective for the Sacramento River downstream of the SRWTP discharge, as illustrated in Figure 1.

In comparison, other dissolved oxygen criteria pertaining to the viability and productivity of sensitive aquatic life species are generally lower levels than the Basin Plan objective. For example, the historic U.S. EPA criterion is as follows (USEPA 1976):

> Freshwater aquatic life: A minimum concentration of dissolved oxygen to maintain good fish populations is 5.0 mg/L. The criterion for salmonid spawning beds is a minimum of 5.0 mg/L in the interstitial water of the gravel.

The current U.S. EPA national dissolved oxygen aquatic life criteria, which are presented in Table 3, are also lower than the Basin Plan objective (USEPA, 1986). As indicated in Table 3, the U.S. EPA dissolved oxygen criteria incorporate averaging periods and are intended to be applied with a frequency of acceptable excursions, which is different from the typical aquatic life criteria of once in three years. "The criteria represent annual worst case dissolved oxygen concentrations believed to protect the more sensitive populations of organisms against potentially damaging production impairment." (USEPA, 1986). However, unlike the U.S. EPA criteria, the dissolved oxygen objectives in the Basin Plan are specified as a minimum number, without reference to averaging period.

Table 3: USEPA Criteria for the Ambient Dissolved Oxygen Concentrations (USEPA 1986).

	Coldwater Dissolved Oxygen Criteria (mg/L)	
Criteria	Early Life Stages[(1)]	Other Life Stages
30 day mean	---	6.5
7 day mean	6.5	---
7 day mean of minimums	---	5.0
1 day minimum[(2)]	5.0	4.0

[1] Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching. For embryonic stages criteria applied to the intergravel water.

[2] Should be considered as instantaneous concentrations to be achieved at all times.

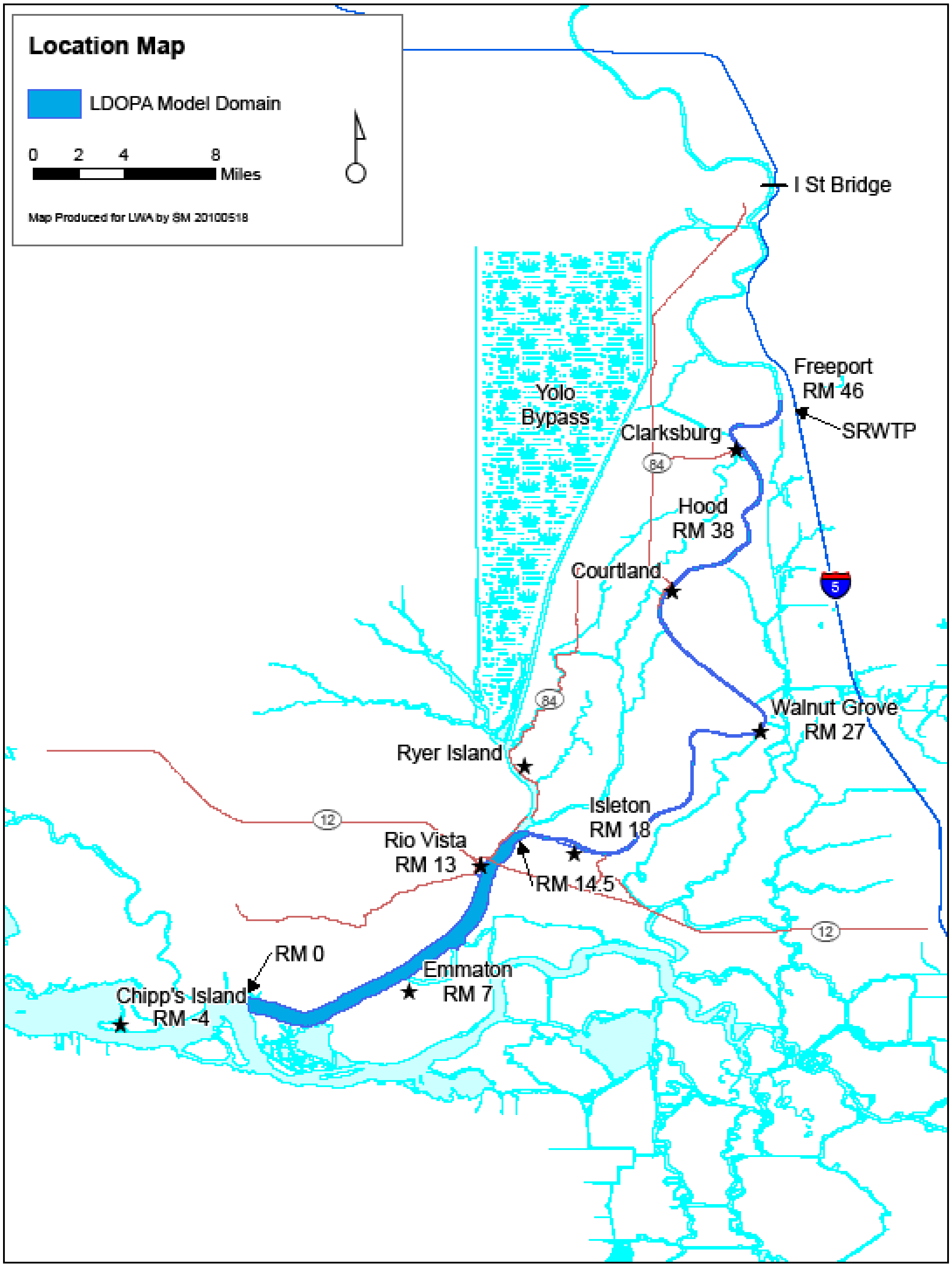


Figure 1: Location Map of the SRWTP Discharge and Points of Interest Downstream on the Sacramento River.

LOW DISSOLVED OXYGEN PREVENTION ASSESSMENT MODEL

The low dissolved oxygen prevention assessment model (LDOPA model) is based on the calculation method originally developed by Streeter-Phelps to model the dissolved oxygen conditions downstream of a wastewater discharge. To form a tractable equation, the Streeter-Phelps model calculates change in the dissolved oxygen deficit which is the difference between the oxygen saturation concentration and the water column concentration. The Streeter-Phelps model relates the rate of change in oxygen deficit with the distance downstream to the respective rates of deoxygenation and reaeration (Tchobanoglous and Schroeder, 1985). In the classic analysis, the consumption of oxygen from the water column through respiration is modeled as a first-order reaction. The replenishment of oxygen to the water column is modeled as a rate proportional to the dissolved oxygen deficit.

A “textbook”, or typical, Streeter-Phelps analysis would not be applicable to the SRWTP because the Sacramento River at the point of discharge is tidally influenced. To simulate the receiving water downstream of the SRWTP discharge, the basic analysis requires a mechanism to address the effluent discharge and diversion pattern due to the tidal cycles so that the critical conditions in the river can be appropriately simulated. Additionally, the textbook analysis only considers one oxygen consuming constituent. For the SRWTP discharge analysis the contribution of carbonaceous and nitrogen oxygen demanding substances is considered. The model developed for the SRWTP analysis is designed to incorporate variable inputs and simulates the discharge/diversion patterns of the SRWTP and the river flows due to the tides. The model simulates a 70-year period of record and is wrapped in a dynamic model framework so that the period of record is simulated repeatedly, with input variables selected from their representative probability distributions to determine a probability distribution for the downstream dissolved oxygen concentrations. The detailed development of the LDOPA model for the current SRWTP analysis is presented in Appendix A.

To determine the respective initial values for the LDOPA model, upstream and effluent flow rate, temperature, dissolved oxygen, CBOD, organic nitrogen, and ammonia are combined with the appropriate mass balance. The variable parameter types used in the Streeter-Phelps model are listed in **Table 4**. Sacramento River flowrate and temperature input values are run as continuous simulation in the dynamic model. The CBOD and ammonia concentrations are combined with the flow rate and appropriate conversion factors to calculate the respective load of ultimate oxygen demand (UOD) in the river at the point of discharge.

Table 4: Input Parameter Types Utilized in the Streeter-Phelps Model.

Parameter	Upstream Ambient	SRWTP Discharge
Flow rate	Hourly time-series input	Monthly Monte Carlo[1,2]
Temperature	Hourly time-series input	Monthly Monte Carlo[2]
Dissolved Oxygen	Calculated saturation[3]	Monte Carlo
Carbonaceous BOD	Monte Carlo	Monte Carlo[2]
Ammonia	Monte Carlo	Monte Carlo[2]
Organic Nitrogen	Monte Carlo	Monte Carlo

(1) Additionally, the discharge flow rate is calculated within the model according to discharge/diversion as necessary for tidal action.
(2) For validation model runs, these parameters input as recorded values.
(3) Upstream dissolved oxygen set equal to the saturation concentration, which is a function of water temperature.

The LDOPA model has been designed to reflect operational practices at the SRWTP. For example, treated effluent from the SRWTP is diverted from the Sacramento River outfall to storage ponds when tidal action reduces the hourly river:effluent flow ratio to a value below 14:1. To account for the diversion of effluent in the model, it tracks the hourly river flow rate over the course of a 24-hour period and determines if discharge is allowed based on the effluent flow rate. The hourly river flow rates are then averaged when discharge is allowed to determine the river flow rate to use in the material balances. Additionally, for the material balances, the effluent flow rate is increased proportionally to the number of hours the effluent is held, so that the volume of effluent treated in a 24 hour period is discharged over the allowable hours of discharge. Because the bulk river flow will move down the river channel at the rate of the daily average flow rate, the river velocity is calculated from the 24-hour average river flow rates.

From the point of discharge at Freeport, river mile 46 (RM 46), to a point downstream of Isleton (RM 14.5), the Sacramento River maintains a relatively constant channel bounded by levees. Downstream of RM 14.5, the river widens significantly and becomes more like an open estuary. This point of change, RM 14.5, is called out on **Figure 1**. To address the change in geometric characteristics, the LDOPA model is set up as two Streeter-Phelps models: one representing the Sacramento River from Freeport (RM 46) to RM 14.5, which feeds into a second one which represents the Sacramento River from RM 14.5 to the confluence of the Sacramento River and San Joaquin River (RM 0).

Because the Streeter-Phelps analysis is based on constant plug flow assumptions, there are limitations associated with the model, including:

- A constant river channel is assumed in each modeled segments, resulting in a constant water velocity over each segment.
- Tidal effects are not directly accounted for on an hourly basis, only the effect of the tides is simulated on a daily average,
- Daily average resolution precludes simulating the diurnal cycles of algal growth,
- Downstream thermal exchange is not considered,

- Longitudinal dispersion is not considered

Taking into account the limitations identified above, the model was validated against measured data at the daily average timescale. Additionally, continuous monitoring for dissolved oxygen in the reach of the Sacramento River studied indicates that the tidal and algal effects within a day are small.

LDOPA MODEL RESULTS

In assessing dissolved oxygen objective compliance in the lower Sacramento River below the SRWTP discharge, it has been determined that the receiving water flow rate and temperature, and effluent CBOD and NBOD concentrations have an effect on downstream dissolved oxygen concentrations. In particular, the ambient Sacramento River flow rate and temperature can greatly affect the dissolved oxygen response in the water column to the SRWTP effluent. For example, greater river flow rate and lower river temperatures result in higher downstream dissolved oxygen concentrations for given effluent conditions.

To protect the beneficial uses and to ensure compliance with the applicable Basin Plan objective, limiting mass loading of oxygen demanding substances in the SRWTP effluent (i.e. load of UOD) is a potential means of preventing low dissolved oxygen levels downstream of the discharge. By limiting UOD load as a means to protect the Basin Plan objective for dissolved oxygen, the SRWTP maintains several different control options to effect changes in downstream dissolved oxygen, including reductions in effluent CBOD and NBOD (ammonia) loadings, and limiting discharge volume seasonally. Reductions in CBOD or NBOD loadings may be accomplished through process optimization, treatment of internal process return flows, increased water recycling, and/or advanced or additional treatment of a portion of SRWTP effluent flow. In the following assessment, the CBOD concentrations are held constant at 110% of the current distribution to approximate current performance and for a small allowance for the effects of future water conservation. The ammonia concentrations are varied between model runs to investigate the effects of modifying NBOD loading on the downstream dissolved oxygen concentrations. Organic nitrogen distributions are maintained at the current levels for all simulations of the model. The assessment considers changes in effluent ammonia levels because process optimization opportunities may be more readily available to effect ammonia reductions than for CBOD reductions. Results from modeled scenarios are compared using the ultimate oxygen demand (UOD) load present in the effluent as defined by Equation (1).

$$UOD = 8.34 \cdot [1.5 \cdot BOD_5 + 4.6 \cdot Ammonia] \cdot Q_{eff} \qquad (1)$$

Where the UOD load is measured in lbs/day of oxygen demand, BOD_5 is in mg/L, ammonia is in mg/L as N, and Q_{eff} is in mgd.

The Streeter-Phelps model was used to determine the combinations of river flow rate and temperature that would maintain compliance with the Basin Plan objective for various levels of UOD in the SRWTP effluent. As the Sacramento River flow rate and temperature are not within the SRCSD's control, the 70 year period record of river conditions based on the Department of Water Resource PROSIM model developed for use in the SRCSD DYNTOX model (SRCSD 2009) serve as the basis to determine the level of UOD in the SRWTP effluent so that dissolved oxygen in the river downstream of the discharge will meet the Basin Plan objective. A discussion of the river flow rates and temperatures for the 70 year period of record in contained in Appendix A.

Utilizing the Streeter-Phelps model over a 70-year period of record for the river conditions, the UOD levels in the SRWTP effluent can be examined iteratively to determine a level at which the dissolved oxygen objectives will be achieved downstream of the discharge. As noted above, the Sacramento River is channelized until just upstream of Rio Vista where the river channel, ship channel, and adjoining sloughs meet. Historic dissolved oxygen monitoring data reveal that the dissolved oxygen at Rio Vista is generally the location for the minimum concentration and the wide, open estuarine areas downstream from Rio Vista receive sufficient reaeration to generally have higher dissolved oxygen compared to Rio Vista.

In determining effluent requirements for SRWTP, the LDOPA model is run to satisfy the Basin Plan objective. Effluent UOD concentrations which yield consistent compliance with the Basin Plan objectives for dissolved oxygen as a function of the SRWTP effluent flow rate are presented in **Figure 2**. As indicated previously, the Basin Plan objective for dissolved oxygen applicable downstream of discharges from the SRWTP is a concentration that shall not drop below 7.0 mg/L. For comparison, effluent UOD concentrations that would maintain receiving water compliance with the dissolved oxygen objective of 7.0 mg/L based on a one day in one-year excursion frequency (a 99.73% compliance) are also included on **Figure 2**. This corresponds to the Basin Plan objective numerical value with the U.S. EPA compliance frequency. Additionally, effluent UOD to maintain the U.S. EPA criteria (USEPA, 1986) listed in **Table 3**, which include minimum instantaneous, 7-day mean, and 30-day mean values are shown on **Figure 2**. For the conditions reflective of the Sacramento River and SRWTP discharge, the U.S. EPA 7-day average dissolved oxygen criterion for the protection of early life stages was found to be the most stringent. As shown in **Figure 2,** The Basin Plan objective results in effluent requirements far more stringent than the most stringent U.S. EPA criterion.

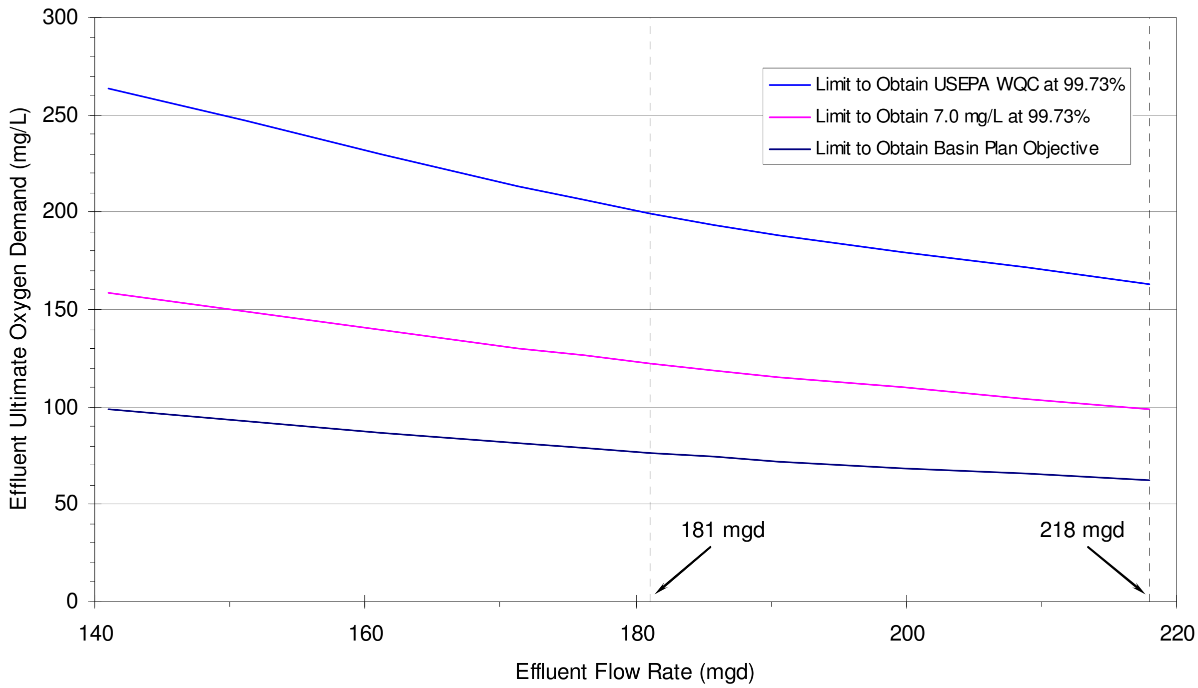


Figure 2: Median Effluent Ultimate Oxygen Demand Concentrations to Obtain Dissolved Oxygen Basin Plan Objective and USEPA Criteria in the Lower Sacramento River. Of the USEPA Criteria for Dissolved Oxygen, the 7-day Average Criterion of 6.5 mg/L for the Protection of Early Life Stages is the Most Limiting.

To investigate the potential seasonality of SRWTP effluent on dissolved oxygen, minimum downstream dissolved oxygen for the current effluent condition is plotted against the corresponding river flow rate and temperature in **Figures 3** and **4**, respectively. The plotted ambient dissolved oxygen concentrations are the model-calculated minimums in the entire domain from Freeport to the confluence with the San Joaquin River for each day in the 70-year period of record. In **Figure 3**, river flow rate conditions less than approximately 20,000 cfs define the potential critical river flow conditions. Similarly, in **Figure 4** ambient dissolved oxygen remains above 8.0 mg/L for all conditions when the Sacramento River temperature is less than 18 °C. River temperatures exhibit a strong seasonality (see Figure 23 Appendix A) leading to the conclusion that dissolved oxygen critical conditions may be seasonal, which is confirmed in **Figure 5** where the 70 year period of record domain minimum dissolved oxygen concentrations are plotted by the corresponding day of the year. **Figure 5** indicates that the May through October time period generally corresponds to critical conditions in the river for low dissolved oxygen concentrations.

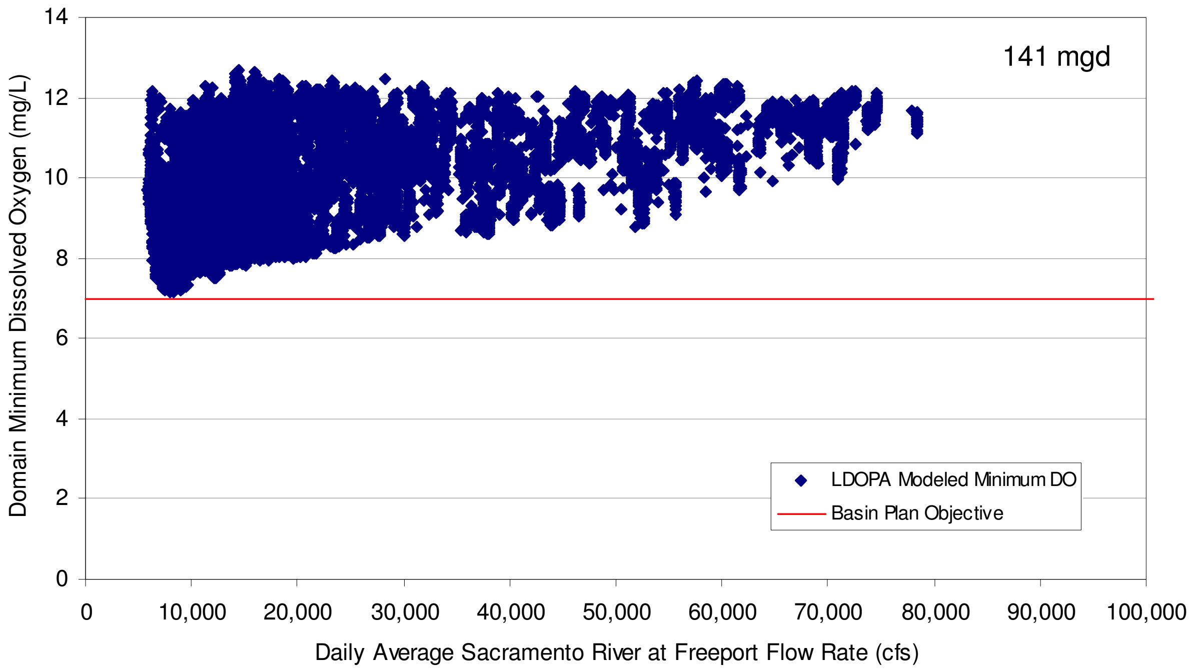


Figure 3: Model Calculated Domain Minimum Dissolved Oxygen Concentration at Corresponding Sacramento River Flow Rate for Current SRWTP Effluent UOD Concentrations at 141 MGD.

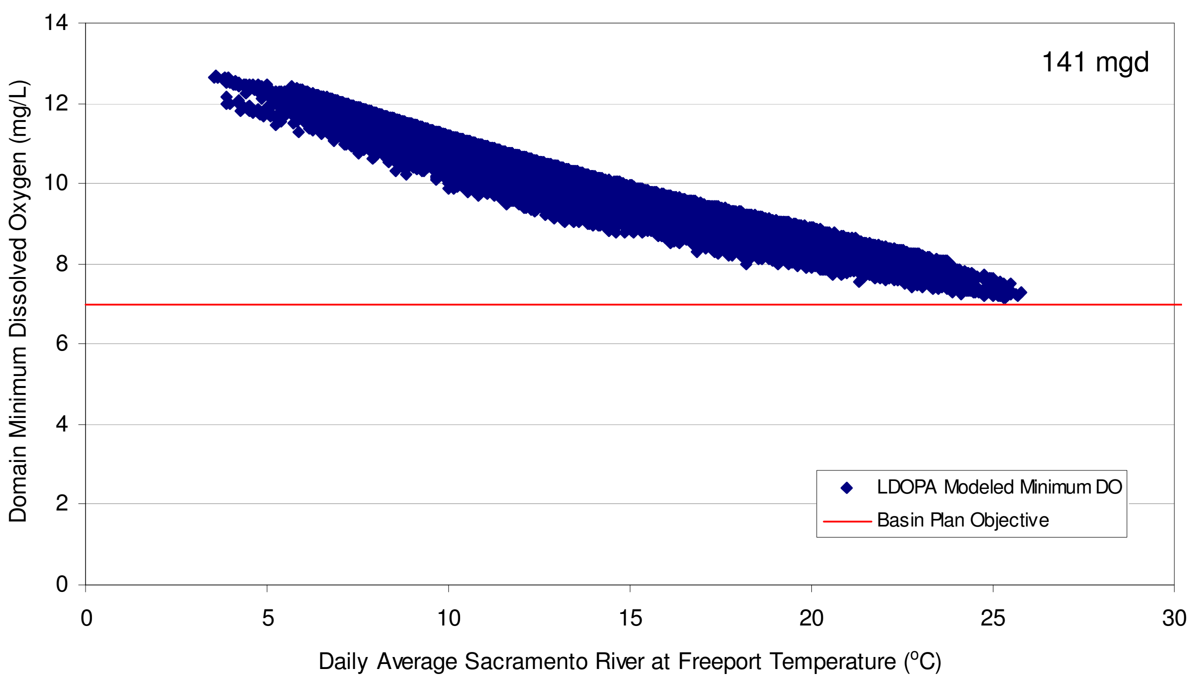


Figure 4: Model Calculated Domain Minimum Dissolved Oxygen Concentration at Corresponding Sacramento River Temperatures for Current SRWTP Effluent UOD Concentrations at 141 MGD.

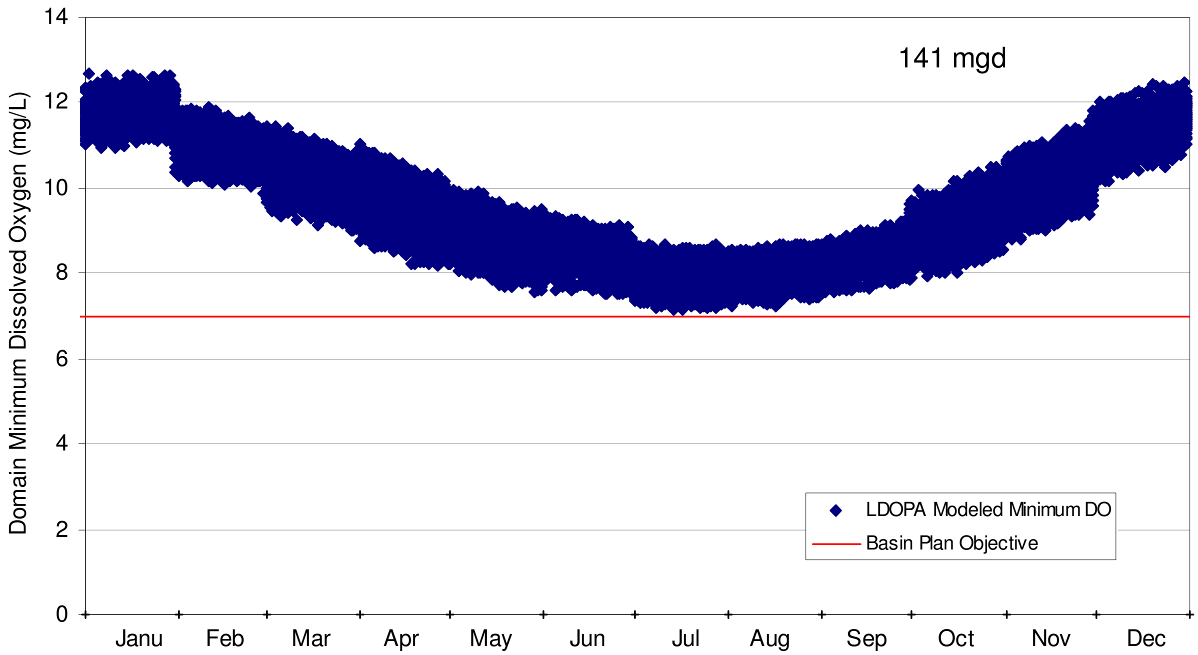


Figure 5: Model Calculated Domain Minimum Dissolved Oxygen Concentration at Corresponding Day of Year for Current SRWTP Effluent UOD Concentrations at 141 MGD.

The current distributions of measured daily and monthly averaged SRWTP effluent UOD load are presented in **Figures 6** and **7** corresponding to the Dry and Wet Seasons, respectively. The relationships between the daily and monthly distributions will be used to calculate the effluent limitations for UOD loading to ensure compliance with the Basin Plan Objective for dissolved oxygen.

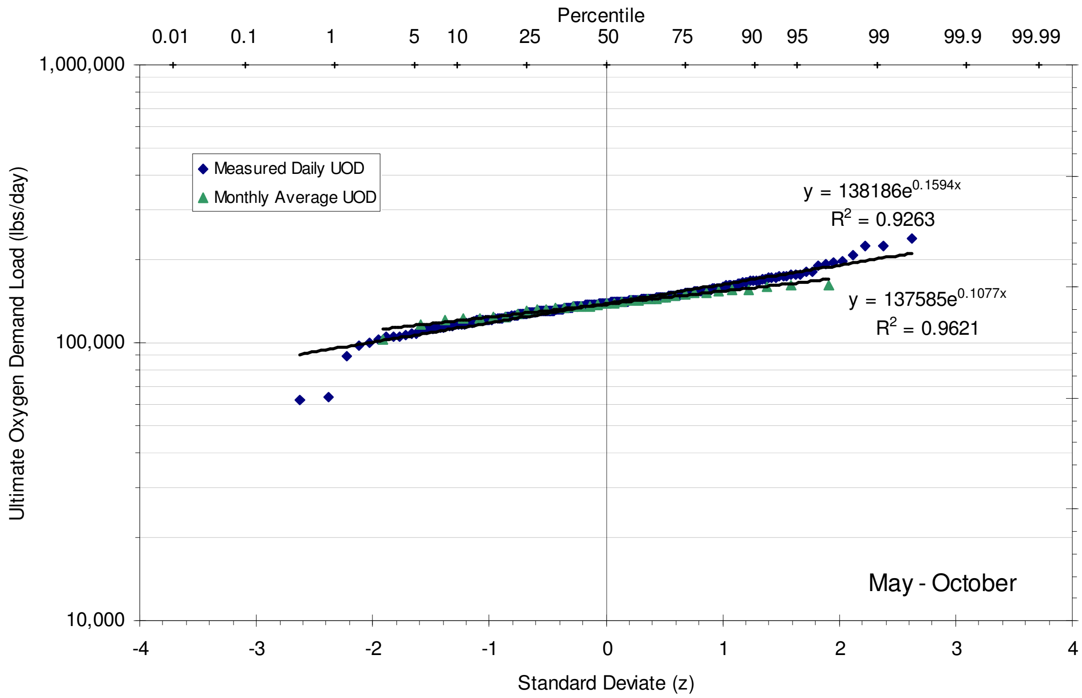


Figure 6: Current Dry Season Ultimate Oxygen Demand Load in SRWTP Effluent.

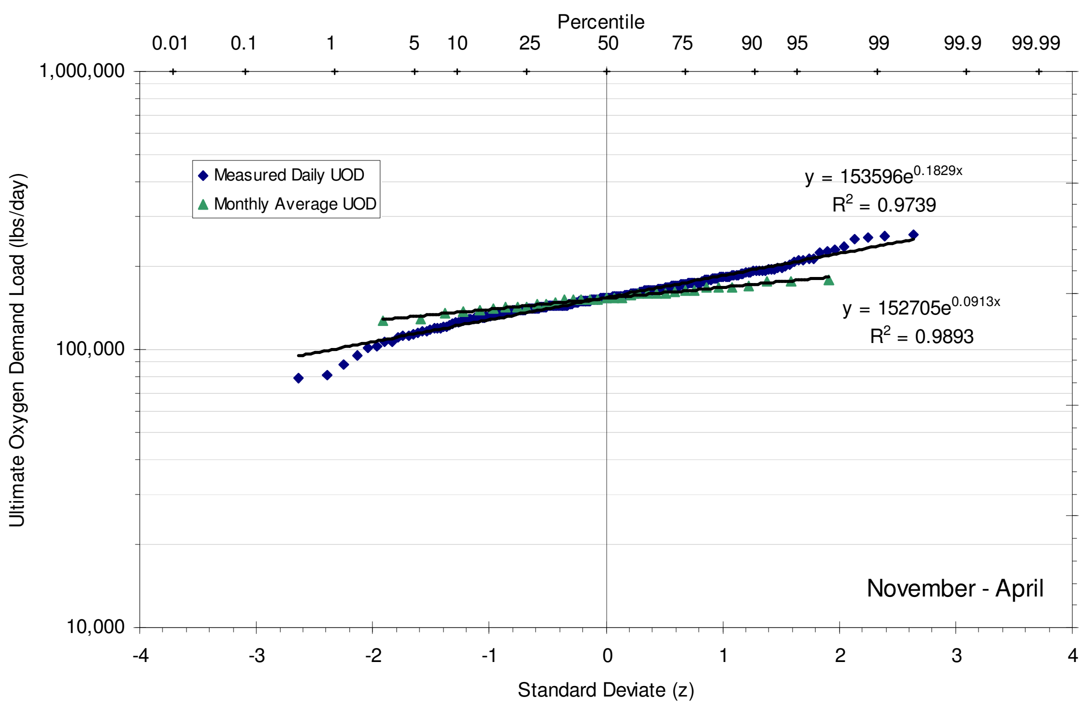
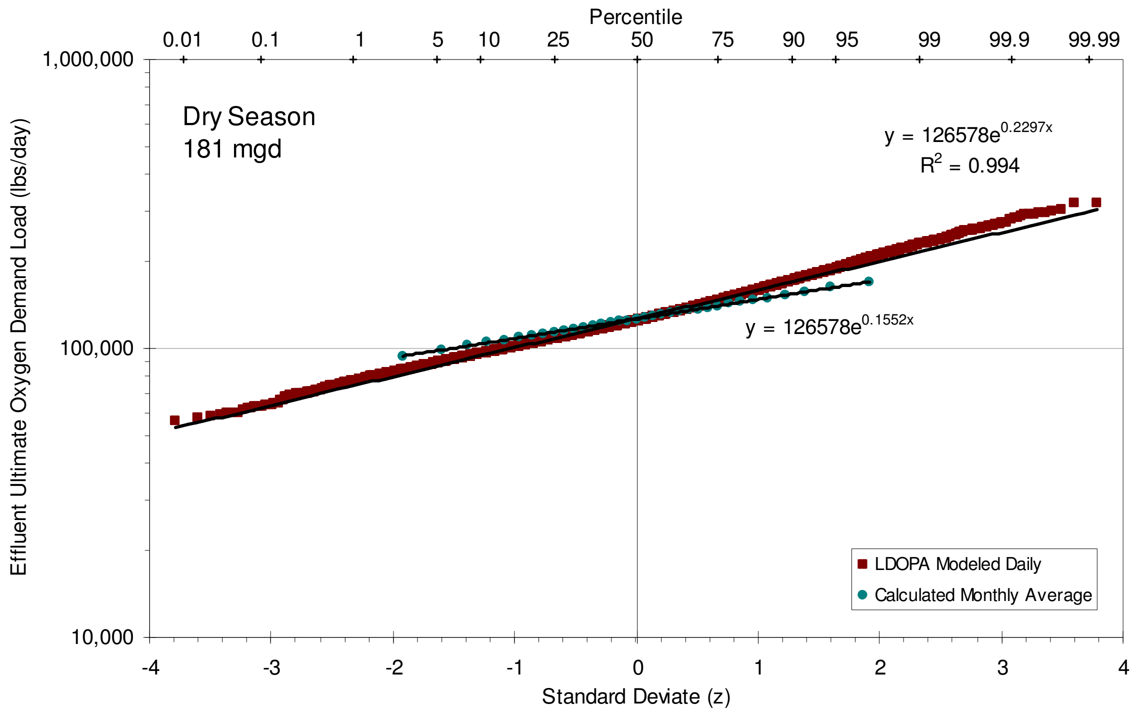


Figure 7: Current Wet Season Ultimate Oxygen Demand Load in SRWTP Effluent.

DISCUSSION

For a given effluent flow rate, the LDOPA model is used to iteratively determine the effluent UOD mass necessary to maintain at least 7.0 mg/L dissolved oxygen in the Sacramento River downstream of the SRWTP discharge for the combinations of river temperature and river flow rate in the 70 year period of record. Because the LDOPA model is a dynamic model running recursively through the 70 year period of record to develop distributions of dissolved oxygen downstream, the target selected for modeling the 181 and 218 mgd scenarios is the minimum dissolved oxygen that has a 95% confidence level to be at least 7.0 mg/L to develop conservative constraints for the SRWTP effluent UOD load. Distributions for effluent loading of UOD are presented in **Figures 8** and **9**. The Dry Season loading of UOD by the SRWTP depicted in **Figure 8** are essentially equal between the 181 and 218 mgd scenarios to maintain the minimum dissolved oxygen of 7.0 mg/L in the river. Wet Season Load of UOD increases proportionally to the increase in effluent flow rate in **Figure 9**.

Time series of minimum dissolved oxygen concentrations in the Sacramento River are presented on **Figures 10** and **11** for SRWTP effluent flow rates of 181 and 218 mgd, respectively. Development of these Figures assumed the CBOD concentrations remain at 110% of current performance and organic nitrogen remained at current performance with the effluent ammonia concentrations reduced to achieve a 95% confidence that the minimum dissolved oxygen concentration would be at least 7.0 mg/L over the 70 year period of record. Moreover, because of the seasonality of river temperature and flow described previously, ammonia is varied in the model from current levels only during the months of May through October. The results are presented as pairs of Figures where the effluent UOD load run for the given flow rate are presented followed by the time series of minimum dissolved oxygen at the 95 percent confidence level. In the Figure sets, the Dry Season extends from May through October and the Wet Season is November through April. The distributions of UOD listed in **Figures 8** and **9** may be used to determine effluent limitations for the SRWTP effluent at 181 and 218 mgd, respectively, for the protection of the Basin Plan objective for dissolved oxygen in the Sacramento River.



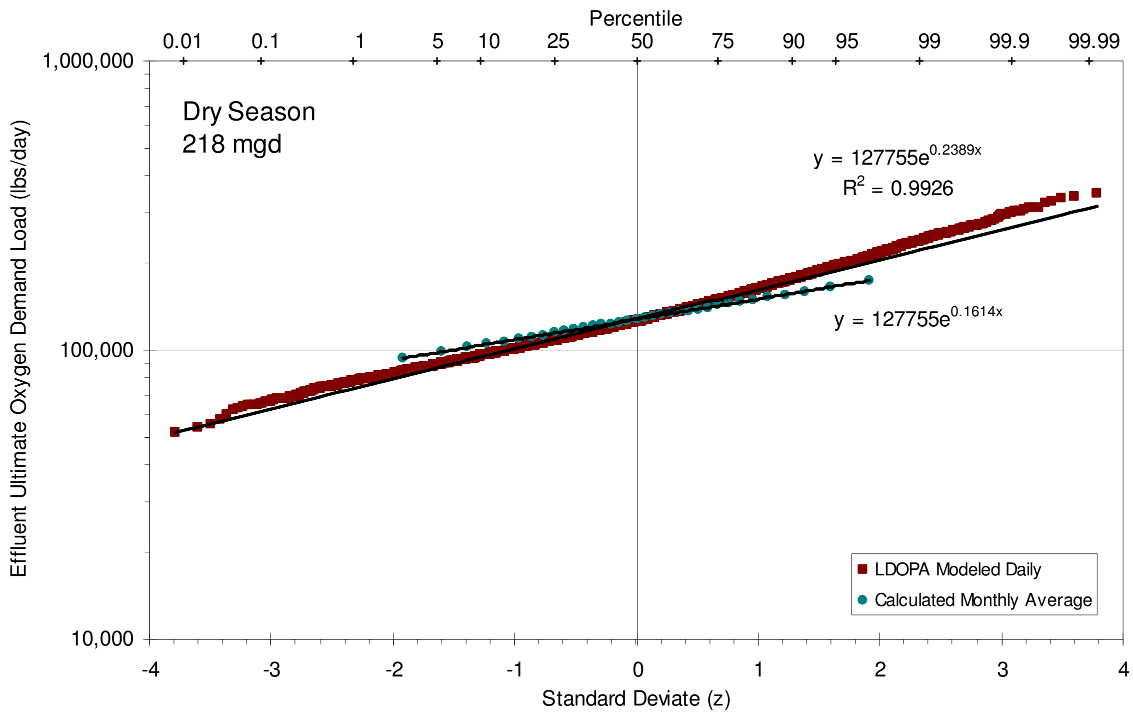
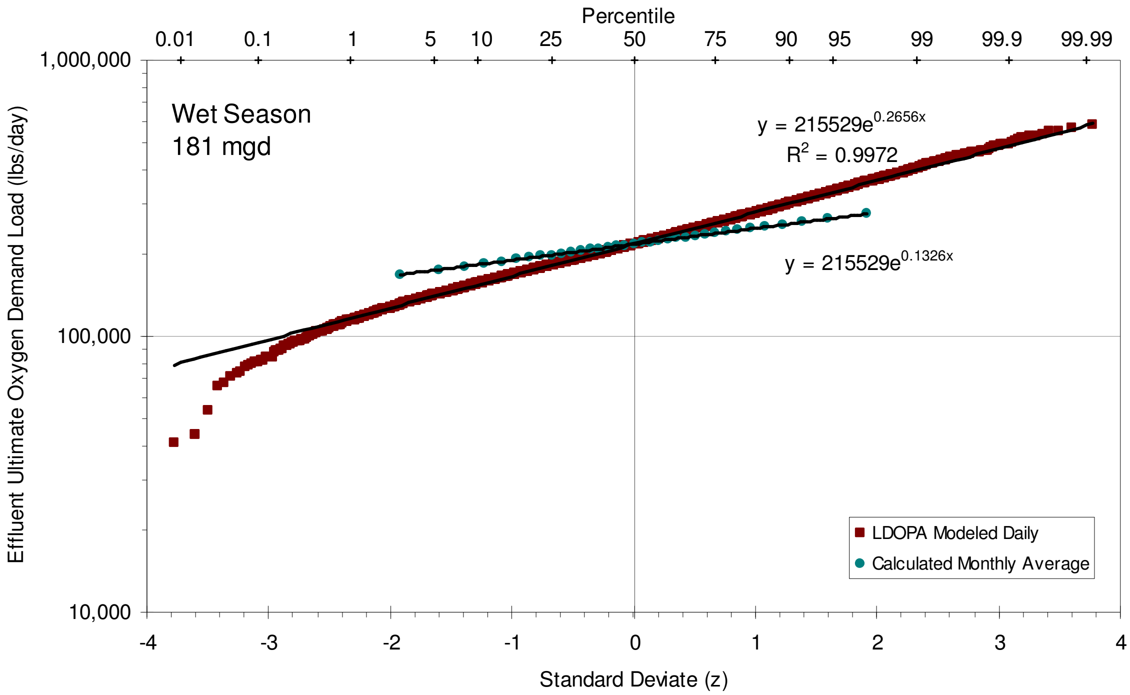


Figure 8: Distribution of Effluent Ultimate Oxygen Load During Dry Season Conditions Corresponding to Maintaining the Basin Plan Objective for Dissolved Oxygen. LDOPA Modeled Daily Distribution from Model Scenario, Calculated Monthly Average using Relationship of Variability in Figure 6



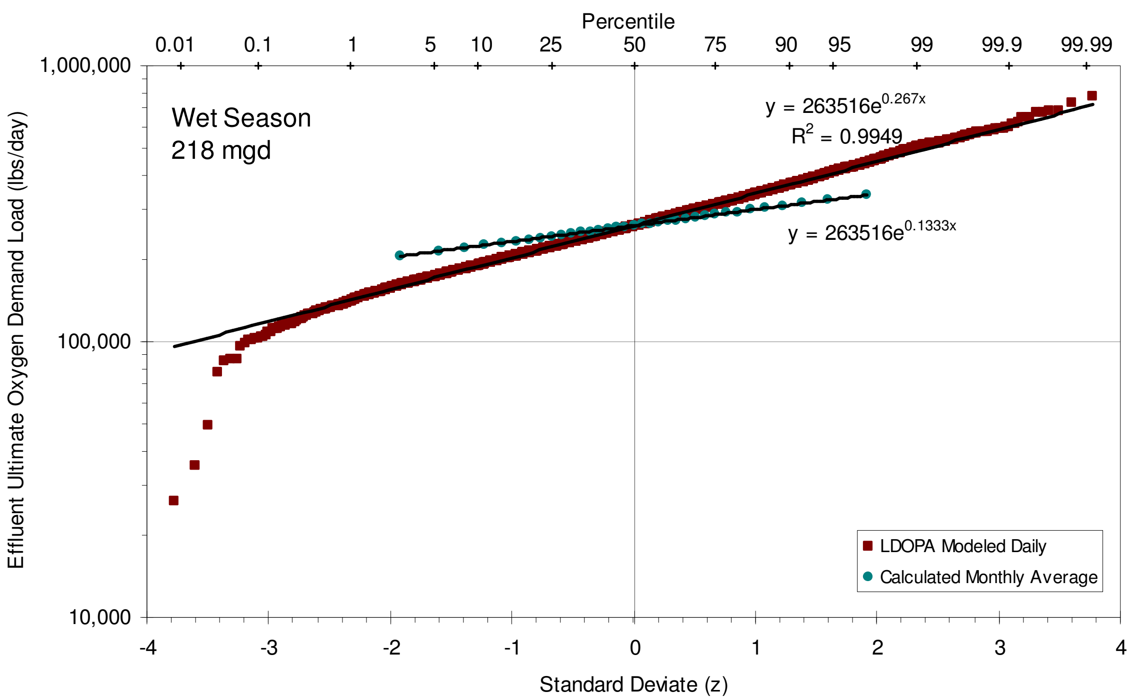


Figure 9: Distribution of Effluent Ultimate Oxygen Demand Load During Wet Season Conditions Corresponding to Maintaining the basin Plan Objective for Dissolved Oxygen. LDOPA Modeled Daily Distribution from Model Scenario, Calculated Monthly Average using Relationship of Variability in Figure 7.

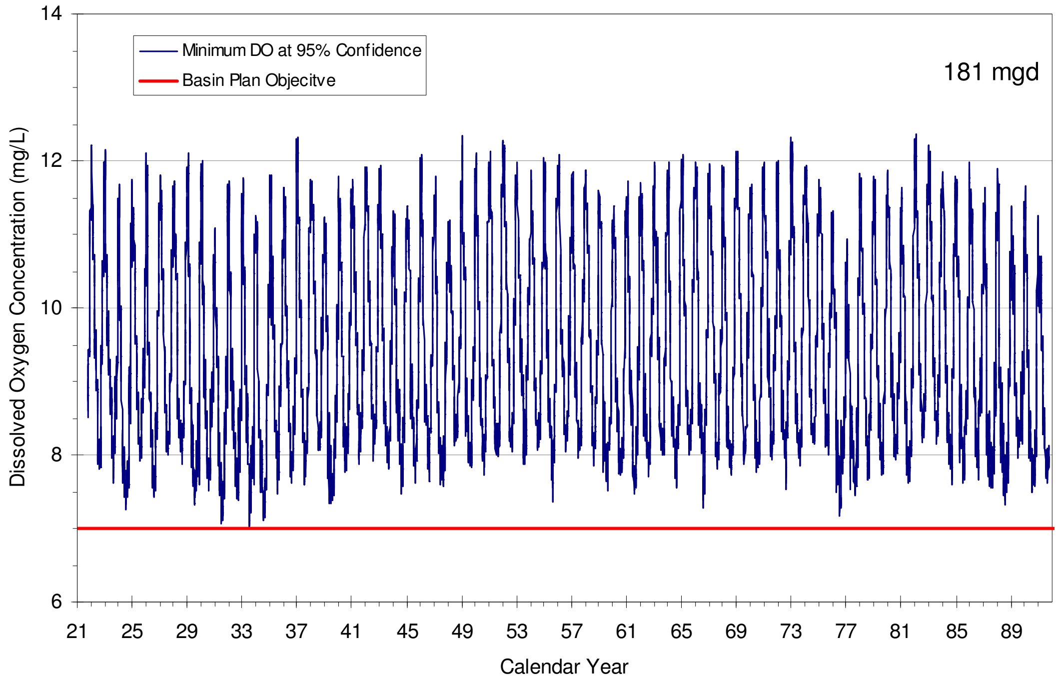


Figure 10: Minimum Dissolved Oxygen Concentrations in the Sacramento River at Prescribed SRWTP Effluent Ultimate Oxygen Demand Loads at 181 MGD.

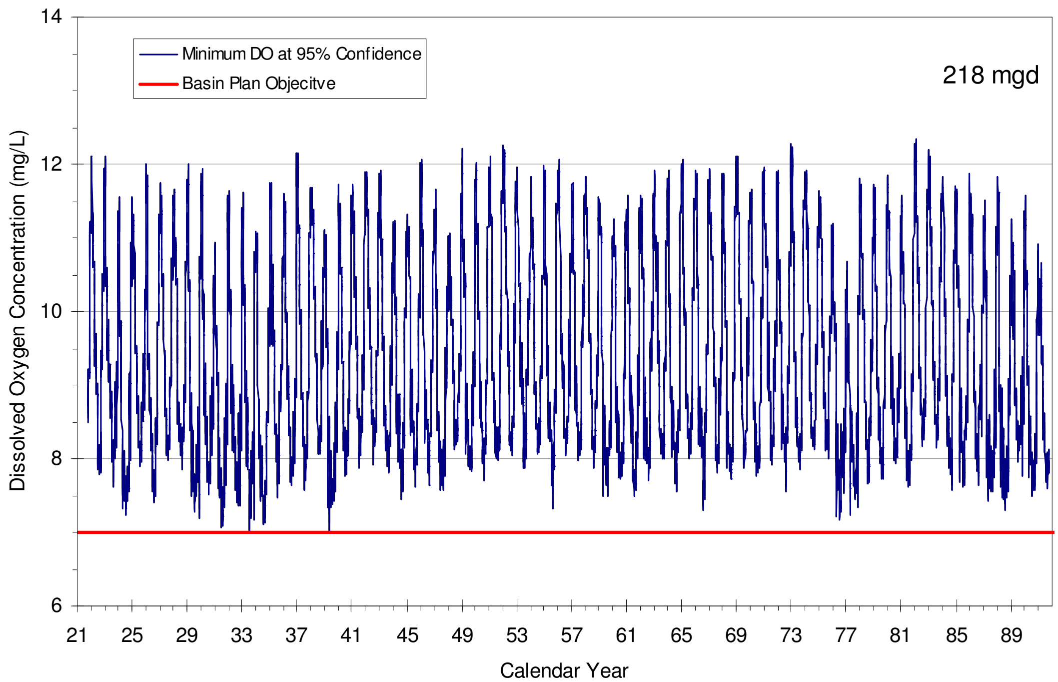


Figure 11: Minimum Dissolved Oxygen Concentrations in the Sacramento River at Prescribed SRWTP Effluent Ultimate Oxygen Demand Loads at 218 MGD.

To assess the effect of seasonality, the 218 MGD UOD curves from **Figure 11** are plotted along with river flow rate and temperatures occurring in the months of May through October in **Figure 12**, corresponding to a Dry Season operating condition. In **Figure 13**, the 218 MGD ammonia curves are plotted along with river flow rate and temperatures occurring in the months of November through April, corresponding to a Wet Season operating condition. In both Figures the minimum dissolved oxygen is at least 7.0 mg/L at the 95% confidence level.

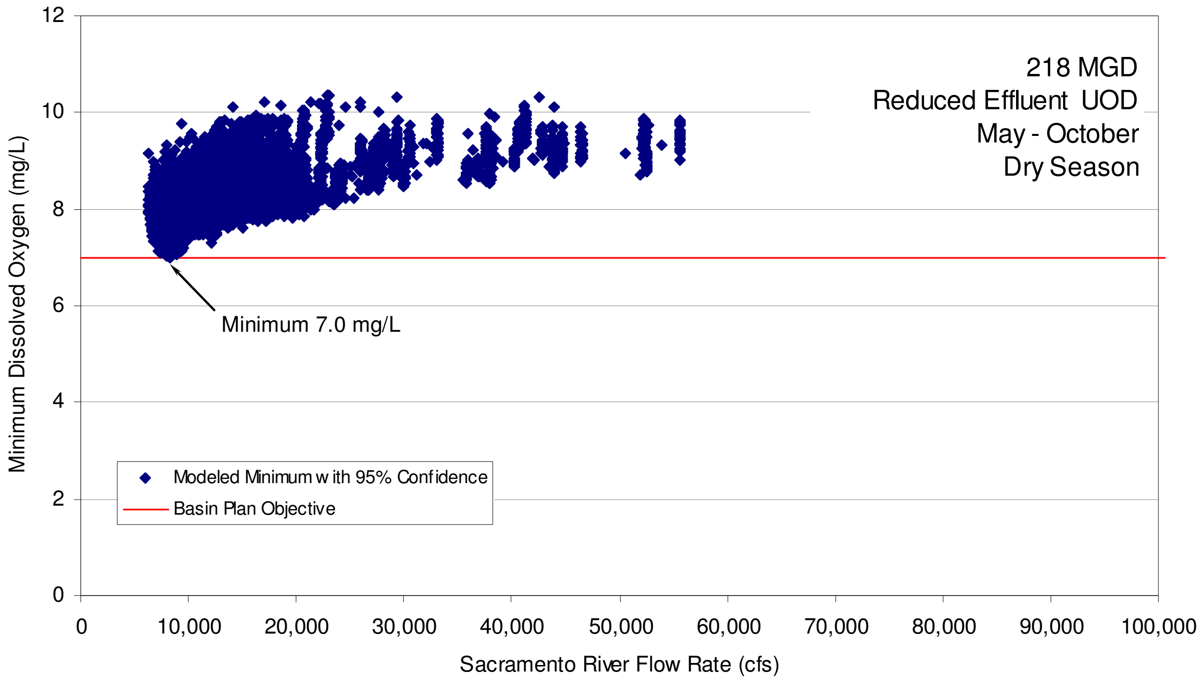


Figure 12: Sacramento River 95% Confidence Minimum Dissolved Oxygen During Dry Season Conditions with Reduced UOD Effluent Load at 218 MGD.

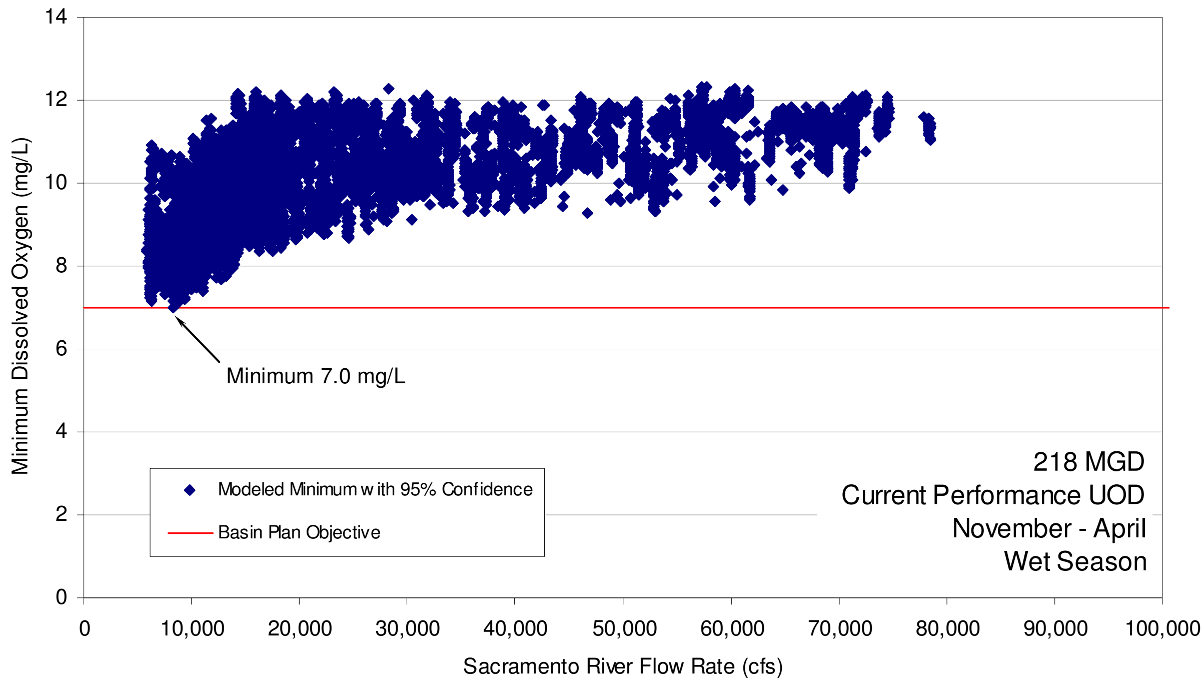


Figure 13: Sacramento River Flow Rate and 95% Confidence of the Minimum Dissolved Oxygen at least 7.0 mg/L Basin Plan Objective at Prescribed SRWTP Effluent UOD Load at 218 MGD.

To maintain compliance with dissolved oxygen objectives, the load of UOD in the effluent must decrease for the Dry Season to maintain the loading of UOD to the Sacramento River. The required distributions of effluent UOD load for the Dry Season are presented in **Figure 8**. In each effluent flow rate considered, the load of UOD in the Dry Season is essentially equal, with a minor increase at higher flow rates due to the larger range in high flow values. The distributions in **Figure 8** provide appropriate information to develop dry season effluent loading limitations for the control of oxygen demanding substances discharged to the river. The Wet Season UOD loadings needed to attain dissolved oxygen objective compliance are depicted in **Figure 9**. Considering strategies to control oxygen demanding substances in the SRWTP effluent, a load limit would encompass all management options available to the District, as opposed to concentration based limits that would need modification based on effluent flow rate or control strategy. For example, increasing water reuse in the dry season would lower the volume of treated discharge, allowing greater UOD concentrations in the effluent, however the allowable UOD loading level would remain unchanged.

The dissolved oxygen sag curve for the Sacramento River downstream of the SRWTP discharge which was developed using the LDOPA model is presented in **Figure 14**. The minimum modeled dissolved concentration occurs at the break point where the Sacramento River changes character from levee bound channel to open estuary. The minimum dissolved oxygen at the 95th percent confidence occurs between Rio Vista and Emmaton. The strong wind induced reaeration is evident between RM 14.5 and the confluence of the Sacramento and San Joaquin Rivers. Variability in the wind speed results in the wider statistical confidence downstream of RM 14.5. **Figure 14** is generated for the model run for 218 mgd, however, because the load of UOD in the effluent controls the minimum downstream dissolved oxygen, the sag curves corresponding to 141 and 181 mgd are essentially identical.

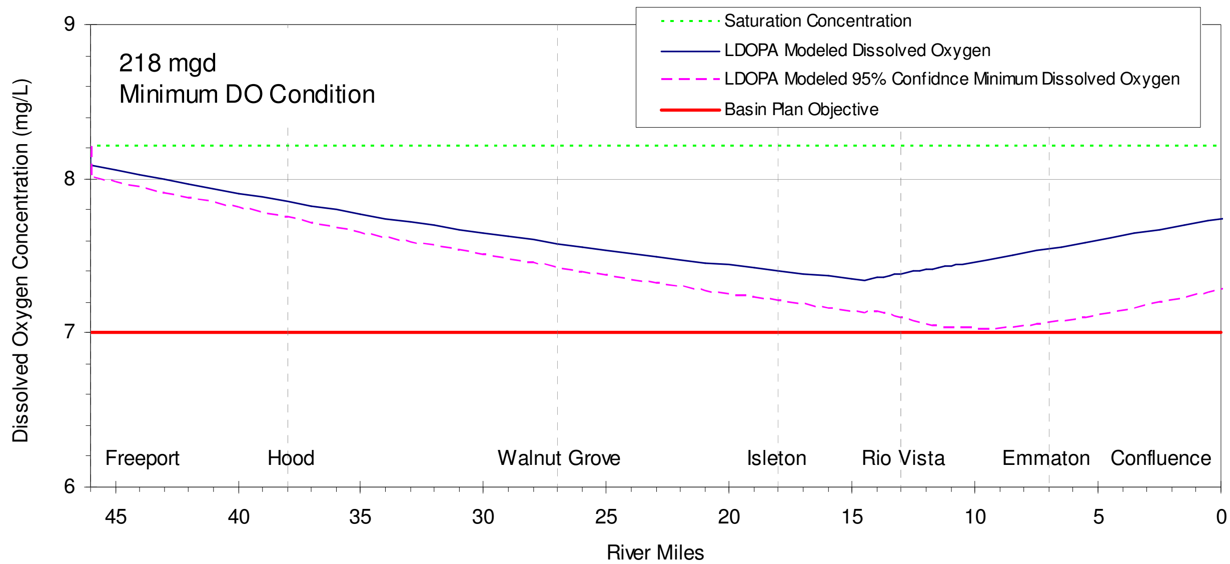


Figure 14: Dissolved Oxygen Sag Curve for the Conditions Resulting in the Minimum Dissolved Oxygen over the Modeled 70 Year Period of Record.

PROPOSED EFFLUENT LIMITATIONS

To provide beneficial use protection that the dissolved oxygen Basin Plan objective is designed to protect in the Sacramento River, the District proposes effluent limitations for Ultimate Oxygen Demand (UOD)[2]. The LDOPA model was used to determine the downstream dissolved oxygen concentrations for varying effluent UOD by maintaining 110% of current BOD_5 concentrations, current organic nitrogen concentrations, and varying ammonia concentrations. The distributions of required effluent UOD loading determined from the model that result in maintaining greater than 7.0 mg/L dissolved oxygen concentrations downstream of the SRWTP discharge with 95% confidence are displayed in **Figure 8** for Dry Season conditions and in **Figure 9** for Wet Season conditions. The LDOPA modeled daily UOD loads are the distribution of daily loads used in the modeling scenario that achieves the Basin Plan objective for dissolved oxygen in the Sacramento River. Using the modeled distributions of UOD, effluent limitations may be calculated to ensure that the effluent quality matches the modeled loads. The maximum daily effluent limitations (MDEL) may be calculated directly from the distributions. Both the dry and wet seasons are 6 months long. In a 5 year permit cycle, there will be 260 samples for each season if the UOD is evaluated twice weekly. The largest measurement in a 260 sample size corresponds to the 99.617th percentile, which is plugged into the equations describing the distributions to calculate the MDEL that ensures the effluent UOD load follows the required distribution. Likewise, in a 5 year permit cycle, there will be 30 monthly average values for both the Wet and Dry Seasons, the largest value corresponding to the 96.774th percentile. The ratio of the exponents in the

[2] The proposed effluent limits for UOD are not intended to be a substitute for BOD and ammonia effluent limitations adopted for other purposes. Effluent limitations would be based on BOD secondary treatment standards, and water quality based effluent limitations for ammonia to protect aquatic life.

equations describing the distributions of the measured daily UOD and monthly average UOD for Dry Season in **Figure 6** and Wet Season in **Figure 7** are used to determine the exponent used to calculate the seasonal average monthly effluent limitations for UOD. The exponents of the equations describing the distributions are the variability in the distributions. The calculated monthly average distributions of UOD load are presented on the Figures with the calculated distribution equation. **Table 5** lists the effluent limitations on effluent UOD loads that would match the levels run in the LDOPA model to satisfy the Basin Plan objectives for dissolved oxygen. A modeling nuance is that there is a slightly greater range in modeled effluent flow rates in the 218 mgd scenario compared to the 181 mgd scenario, the 218 mgd Dry Season effluent limitations are technically slightly greater[3] than the 181 mgd limitations. The most conservative approach is to use the 181 mgd Dry Season limits for the 218 mgd case, maintaining Dry Season loading for both discharge scenarios. **Figure 15** is a presentation of the ammonia and BOD_5 concentrations corresponding to the UOD AMEL and MDEL limitations listed in **Table 5**. Effluent limitations for BOD_5 based on secondary treatment standards and ammonia based on the protection of aquatic life are listed in **Table 6**. Ammonia water quality based effluent limitations are developed based on an acute mixing zone of 60 feet, a chronic mixing zone of 350 feet, and the DYNTOX model.

Table 5: Proposed Ultimate Oxygen Demand Effluent Limitations.

Q_{eff}	Percent Compliance[(1)] (%)	Dry Season UOD[(2)] (lbs/day)		Wet Season UOD[(2,3)] (lbs/day)	
		AMEL	MDEL	AMEL	MDEL
181	99.9885	192,000	234,000	307,000	438,000
218	99.9879	192,000	234,000	376,000	537,000

(1) Percent of time the LDOPA model calculates the downstream receiving waters will comply with the Basin Plan Objective of 7.0 mg/L of dissolved oxygen.

(2) Ultimate Oxygen Demand = $8.34*[1.5*(BOD_5) + 4.6*(\text{Ammonia})]*Q_{eff}$; BOD5 in mg/L, ammonia in mg/L as N, and Q_{eff} in mgd.

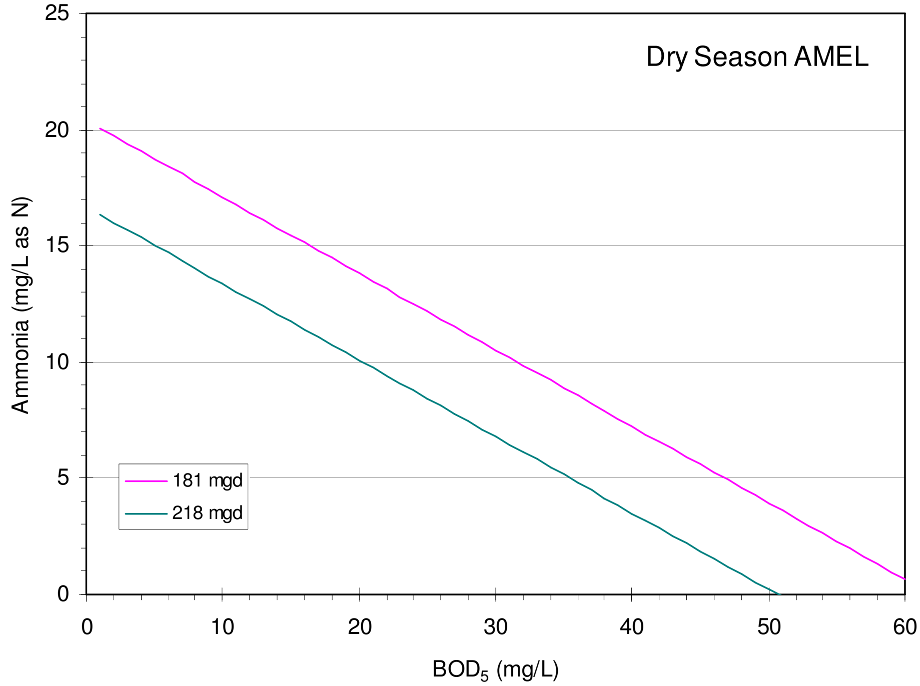
(3) Wet Season UOD set to Current Performance

Table 6: Proposed Concentration Based Effluent Limitations for BOD_5 and Ammonia.

Parameter	Units	Effluent Limitations: Average Monthly	Average Weekly	Maximum Daily
BOD_5	mg/L	30	45	60
Ammonia[(1)]	mg/L as N	37	---	47

1 Based on acute mixing zone of 60 feet and chronic mixing zone of 350 feet as evaluated with DYNTOX dynamic model.

[3] 218 mgd Dry Season effluent loading limitations are calculated to be AMEL 197,000 lbs/day, and MDEL 242,000 lbs/day.



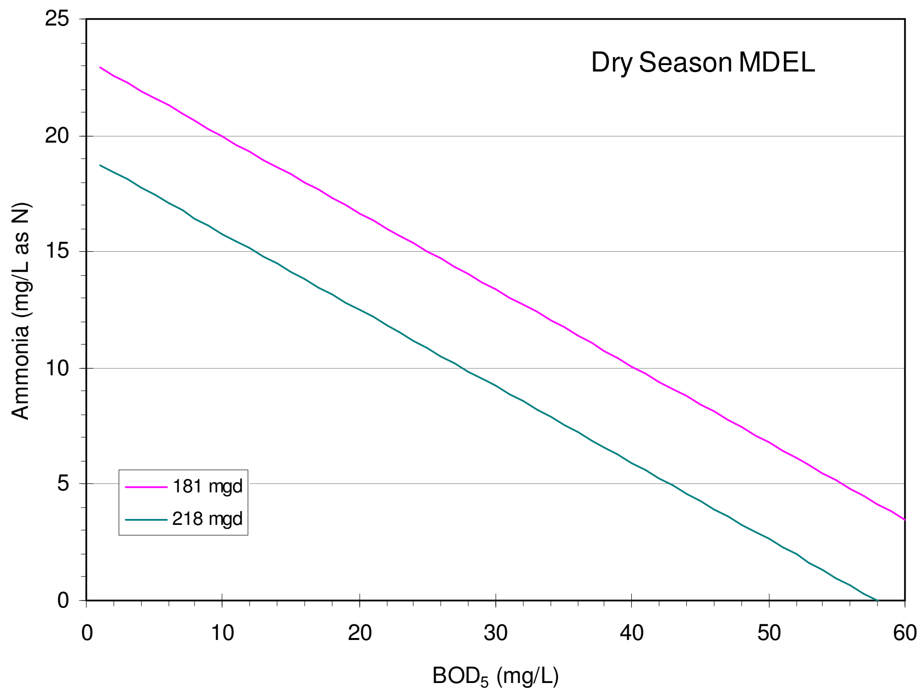


Figure 15: Relationships Between Effluent Ammonia and BOD_5 to Maintain Compliance with the Ultimate Oxygen Demand Effluent Limitations Proposed in Table 5.

CONCLUSIONS

The Streeter-Phelps model developed to analyze the dissolved oxygen concentrations has been utilized to assess the viability of modifying loads of oxygen demanding substances in effluent so that the SRWTP will continue to meet dissolved oxygen objectives in the Sacramento River. Validation of the developed model (Appendix A) has demonstrated that the model approximates the measured dissolved oxygen downstream of the SRWTP discharge.

To maintain compliance with dissolved oxygen objectives to the UOD load in the SRWTP effluent should be limited. One way to achieve UOD limitations is to control the CBOD and/or NBOD concentrations in the SRWTP effluent. Increased recycled water is also an effective method to limit the load of UOD discharged river.

Seasonal operations or controls are evaluated as the Dry Season condition spanning May 1st through October 30th as displayed in **Figure 12**, and a Wet Season operating condition spanning November 1st through April 30th as displayed in **Figure 13**. These figures show that it is the combination of lower river flow rate and higher river temperature that form the conditions where dissolved oxygen may potentially become an issue downstream. While seasonal control of effluent ammonia and BOD concentrations could be one method for ensuring compliance with dissolved oxygen levels in the Sacramento River[4], limitations of the UOD load for Dry and Wet Seasons provide the least ambiguous method to control oxygen demanding substances in SRWTP effluent to ensure compliance with the Basin Plan objective for dissolved oxygen.

Management Options

The information presented in this report could serve as the basis for management of UOD levels over a period of increasing discharge. The District has recognized that efforts are needed in the future to reduce the SRWTP's potential impact on episodic summer occurrences of low dissolved oxygen in the lower Sacramento River as the effluent discharge increases. These episodic occurrences can be eliminated through various, or combinations of, options including process optimization, treatment of internal return flows, expansion of the District's water recycling program, or additional treatment of a portion of the SRWTP effluent flow. Each option reduces the load of oxygen demanding substances in the SRWTP discharge. Future refinements of the model or more detailed modeling could be used to extend the results presented here once control alternatives have been established. But, for each scenario, the Dry Season allowable loading would be limited to levels presented in **Figure 8**.

To date, the District has initiated process optimization efforts that are expected to lower the SRWTP's effluent ammonia levels in the near term and has initiated an evaluation of the treatment options and costs of treating internal return flows that contain ammonia. In addition, through its Water Recycling Opportunities Study, the District continues to seek viable projects although cost effective water recycling projects have not yet been identified.

REFERENCES

Sacramento Regional County Sanitation District (SRCSD 2009), "Administrative Draft Antidegredataion Analysis for Proposed Discharge Modification for the Sacramento Regional Wastewater Treatment Plant", May 20, 2009, prepared by Larry Walker Associates.

[4] The Wet Season operating condition could tolerate effluent ammonia concentrations in excess of 30 mg/L as N up to 218 MGD. Dry Season operating conditions would dictate annual average effluent ammonia concentrations of 14 mg/L as N for 181 MGD and ammonia concentrations of 11 mg/L as N for 218 MGD to achieve the Basin Plan objective for dissolved oxygen.

Tchobanoglous and Schroeder (1985), *Water Quality*, Addison-Wesley Publishing Company, Inc., Reading, MA.

USEPA (1976), Quality Criteria for Water (the Red Book), Stock No. 055-001-01049-4, July 1976.

USEPA (1986), Ambient Water Quality Criteria for Dissolved Oxygen, EPA 440/5-86-003, April 1986.

Page intentionally blank

APPENDIX A: STREETER-PHELPS MODEL DEVELOPMENT FOR DISSOLVED OXYGEN BELOW THE SRWTP DISCHARGE

The Sacramento Regional Wastewater Treatment Plant (SRWTP) discharges secondary treated disinfected effluent to the Sacramento River at Freeport. A location map for the point of discharge and points of interest downstream on the Sacramento River is presented in Figure 1. The general method of Streeter-Phelps is utilized to model the dissolved oxygen in the Sacramento River downstream of the SRWTP outfall. The classic Streeter-Phelps equation only considers oxygen depletion by one oxygen demanding parameter and reaeration of oxygen via surface transfer with the atmosphere. The classic equation could be employed in the analysis of the Sacramento River, but would require the carbonaceous and nitrogenous oxygen demands and the rates they are oxidized to be lumped into a single total ultimate oxygen demand. To assist in the analysis of the SRWTP discharge and evaluation of the separate carbonaceous and nitrogenous affects on dissolved oxygen, the classic Streeter-Phelps equation is expanded to include oxygen depletion of dissolved carbonaceous oxygen demanding compounds, particle associated carbonaceous oxygen demanding compounds, and ammonia present in the water column. Additionally, the decay of organic nitrogen in organic matter into ammonia is included in the expanded Streeter-Phelps model. The detailed development of the expanded Streeter-Phelps equation is presented in Appendix B.

The Streeter-Phelps model combines the flow rate, temperature, dissolved oxygen concentration, carbonaceous biochemical oxygen demand, nitrogenous biochemical oxygen demand, and organic nitrogen concentration from the upstream river and the treated effluent discharge to determine the initial conditions at the point of discharge. Using river flow velocity, and the rates of oxygen reaeration and consumption, the model calculates the downstream oxygen deficit. From the point of discharge at Freeport (RM[5] 46) to downstream of Isleton (RM 14.5), the Sacramento River is channelized flowing between levees. Downstream of RM 14.5, the Sacramento River widens and becomes more estuary like for the downstream reach. To model both segments, the LDOPA model first calculates conditions in the river-like portion from Freeport to just below Isleton and using the calculated conditions just below Isleton as input the LDOPA model then calculated conditions in the estuary-like portion from below Isleton to Chipps Island. In the model, the relationship between river flow rate and water velocity are held constant between Freeport and RM 14.5. In the estuary segment of the river downstream of Isleton, as is discussed below, the measured velocity correlates well to the flow rate at Freeport. The low dissolved oxygen prevention assessment (LDOPA) model calculates daily averaged dissolved oxygen in the receiving water downstream of the SRWTP discharge to the confluence of the Sacramento and San Joaquin Rivers for the period of record of available river flow rates and temperature.

To determine the required effluent limitations of oxygen demanding compounds in the SRWTP discharge, the variability of effluent parameters are evaluated in the model by looping the model over the period of record and selecting from the statistical distributions representing the parameters. Using the LDOPA model in a dynamic fashion allows the effluent variability to be evaluated as well as statistical confidence to be calculated for the downstream dissolved oxygen

[5] River Miles from confluence of Sacramento River and San Joaquin River.

concentrations. The remainder of Appendix A is a description of the model inputs and rates used to simulate the Sacramento River downstream of the SRWTP discharge.

Sacramento River Characteristics

The Sacramento River characteristics of flow rate, channel geometry, and water quality are important parameters to the dissolved oxygen model. River flow rate effects the dilution of effluent and the speed at which the mixed effluent moves downstream.

Sacramento River Flow Rates

The Sacramento River watershed extends through the northeastern quarter of California and is comprised of a heavily managed system of reservoirs and diversions along the main stem and tributary systems. Monthly average flow rates for calendar years 2001 through 2008 are presented in Figure 16. Typically, summer flow rates exceed 10,000 cfs, however in more critical water years the monthly average flow rates may drop below 10,000 cfs. The harmonic mean flow rate of the Sacramento River at Freeport is 15,800 cfs based on recorded daily average flow rates from October 1969 through September 2009, reflecting the period with all major reservoirs in operation in the watershed.

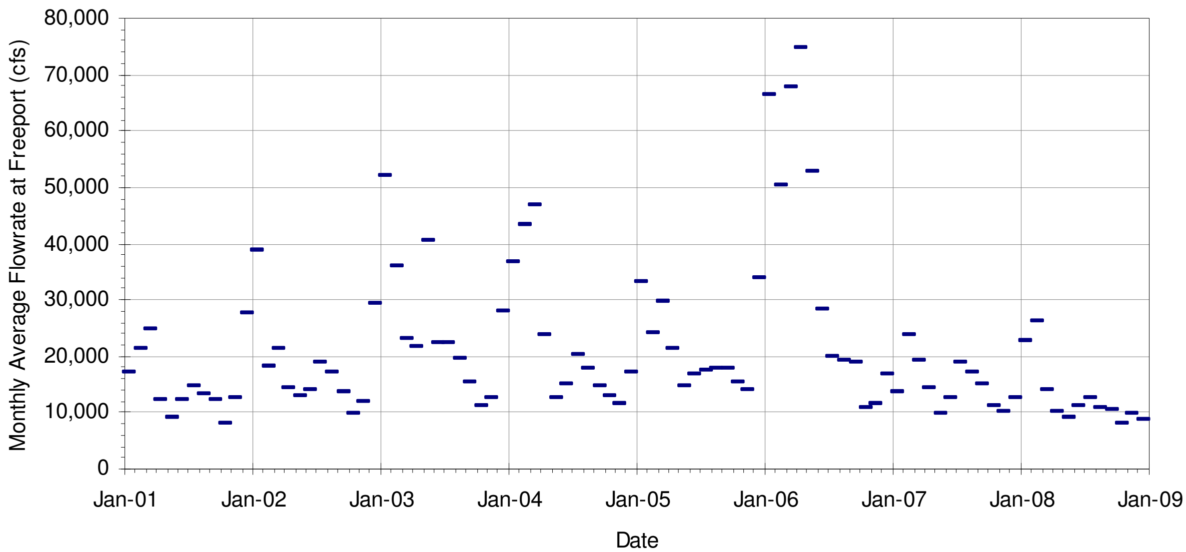


Figure 16: Monthly Average Sacramento River Flow rate at Freeport.

The Sacramento River is used by the Central Valley Project (CVP) and State Water Project (SWP) as a conduit to convey water stored in reservoirs to the Delta and export pumping facilities. The operation of the reservoirs generally controls the summer and fall river flow rates, and hydrologic conditions generally control the winter and spring flows. Department of Water Resources (DWR) models are used to calculate the river flow rates that would occur based on current or projected water needs and operations based on the historical meteorology. To assess the critical conditions for dissolved oxygen, the hourly river flow rates from 1922 through 1991 generated by the DWR PROSIM model for use in the SRCSD DYNTOX model (SRCSD 2009) serve as the period of record. The daily averaged flow rates from the SRCSD DYNTOX model are presented in Figure 17. Note the hourly flow rates are used as input to the LDOPA model, the daily averaged values are displayed for clarity. To illustrate the hourly flow patterns, flow rate data obtained from USGS station 11447650 are presented in Figure 18. USGS data are available as 15-minute average and daily average. Hourly data were formed by aggregating the raw 15-minute average USGS data.

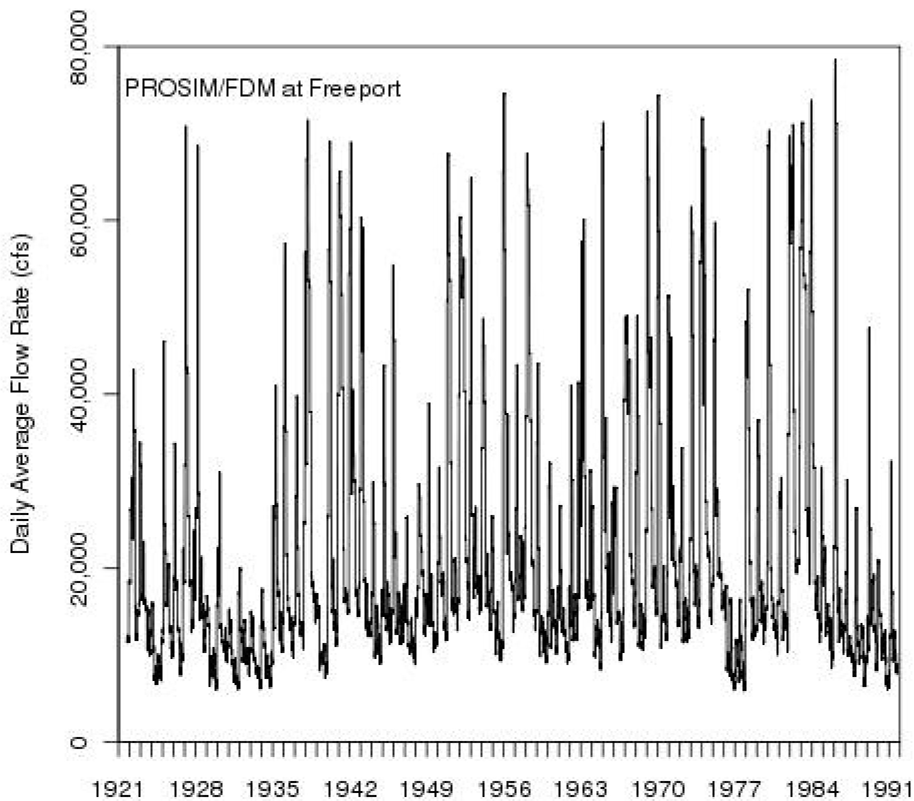


Figure 17: PROSIM Calculated Sacramento River Daily Average Flow Rates at Freeport for the Period of Record Water Year 1922 through 1991.

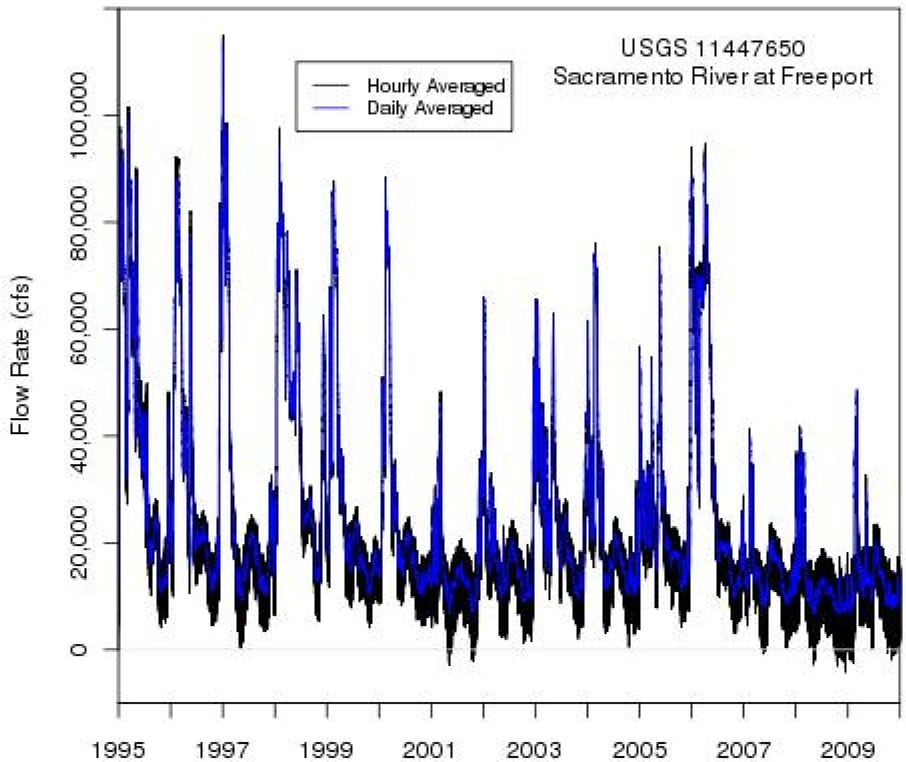


Figure 18: Sacramento River Flow Rate at Freeport Recorded by USGS Station 11447650.

Discharge from the SRWTP is diverted to storage ponds when tidal action reduces the effective river flow rate to the point of a 14:1 dilution ratio which corresponds to 3,000 to 5,000 cfs for effluent flow rates of 141 to 218 mgd, respectively on Figure 18. To account for the holding of effluent, over the course of a 24 hour period the model tracks the hourly flow rate and determines if discharge is allowed based on the effluent flow rate. The hourly river flow rates where discharge is allowed are averaged to determine the river flow rate to use in the material balances. Additionally, for the material balances, the effluent flow rate is increased proportionally to the number of hours the effluent is held, so that the desired volume of effluent is discharged over the allowable hours of discharge. Because the bulk river flow will move down the river channel at the rate of the daily average flow rate, the river velocity is calculated from the 24-hour average (daily average) river flow rates using relationships discussed below.

Sacramento River Channel Geometry Freeport to Isleton

The channel geometry determines the depth and velocity of the river for given river flow rates. As both water depth and velocity are parameters in the model, and a long term record is available only for flow rate, the relationships determined by the channel geometry can be used to develop the long term record of water depth and velocity. USGS[6] maintains a station at Freeport with flow rate, stage, and velocity determined as 15 minute averages. The period of record of the 15 minute average velocity and stage data were obtained directly from USGS, as the velocity data available from CDEC[7] after October 1, 2007 seem to follow a different relationship from the data collected prior. Daily averaged river stage data from December 2, 2001 to January 08, 2010 are converted to river depth and presented in Figure 19. A regression between river flow rate and river depth (feet) for use in the model is presented in Equation (2).

$$d = \begin{cases} 15.0 + \exp\{0.2124 \cdot \ln(Q) - 0.006\}; \; Q < 13{,}400 \text{ cfs} \\ 15.0 + \exp\{0.207 \cdot [\ln(Q)]^2 - 3.6861 \cdot \ln(Q) + 18.339\}; \; 13{,}400 \text{ cfs} < Q < 59{,}000 \text{ cfs} \\ 15.0 + \exp\{10.519 \cdot \ln(\ln[Q]) - 22.381\}; \; Q > 59{,}000 \text{ cfs} \end{cases} \tag{2}$$

Where the water depth, d, is in feet; and the flow rate, Q, is in cfs.

The water velocity can be calculated by dividing the flow rate by the channel depth calculated by Equation (2) and channel width calculated with Equation (3).

$$w = 535 + (d - 20.8) \cdot 2.3 \tag{3}$$

Where the effective channel width, w, is in feet.

To determine the constants in Equation (2) and the relationship between the stage and water depth, the velocity calculated from the depth regression was compared to the measured water velocity as displayed in Figure 20. The stage data were converted to depth data by minimizing the sum of squares between the measured and calculated daily averaged velocities. Subtracting 80.827 feet from the stage data results in the minimum sum of squares and is incorporated in Equation (2) for the river depth. The velocity is calculated by Equation (4). The calculated daily average velocity from Equation (4) is superimposed on the daily averaged measured velocity data from December 2, 2001 to January 08, 2010 in Figure 20.

$$u = \frac{Q}{w \cdot d} \tag{4}$$

Where is the velocity, u, is in feet/sec.

[6] http://waterdata.usgs.gov/nwis/uv?site_no=11447650
[7] http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=FPT

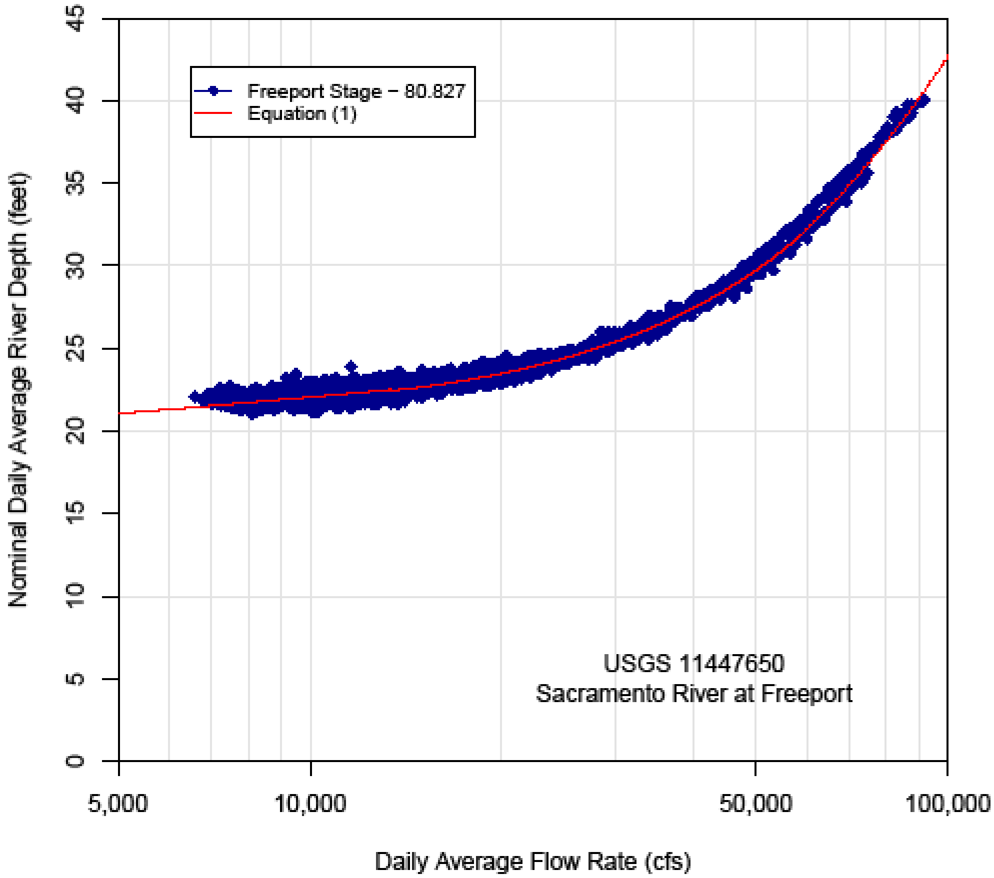


Figure 19: Nominal River Depth at Freeport as a Function of the Daily Average Flow Rates Measured at Freeport.

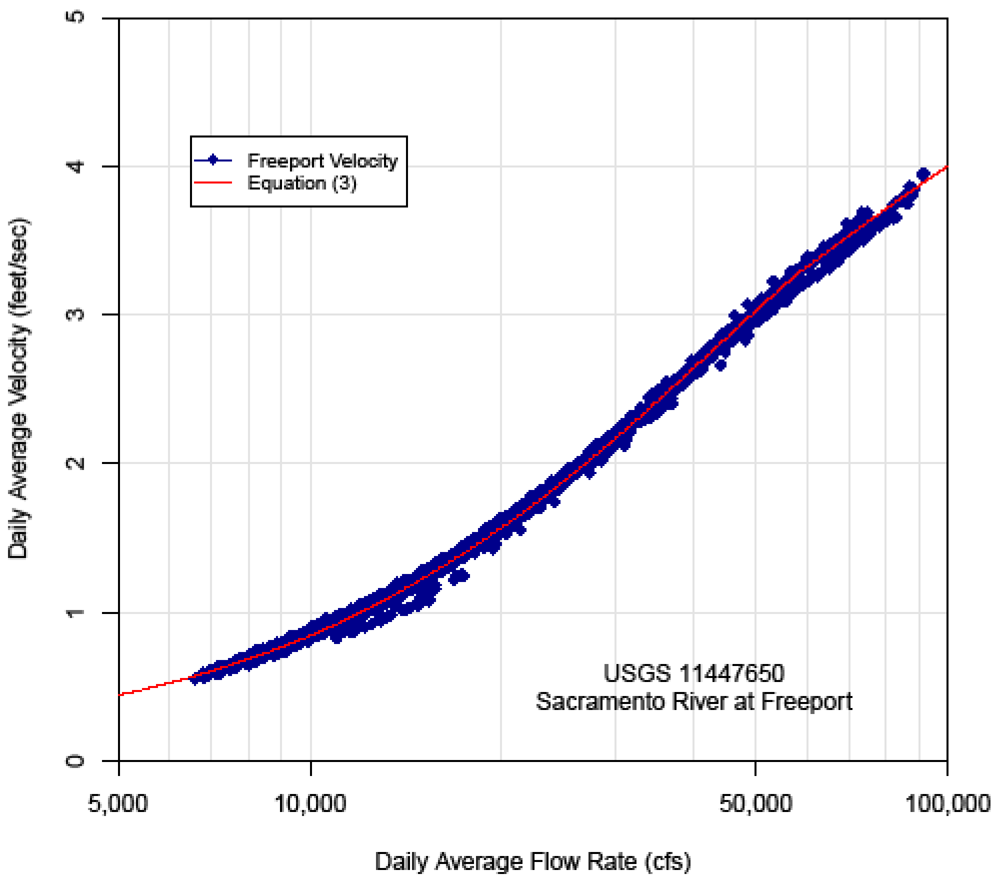


Figure 20: Sacramento River Daily Average Velocity at Freeport as a Function of the Corresponding Daily Average Flow rate.

Sacramento River Channel Isleton to Confluence of San Joaquin

USGS[8] maintains a station at Rio Vista with flow rate, stage, and velocity determined as 15 minute averages. The period of record of the 15 minute average velocity and stage data were obtained directly from USGS. Additionally, USGS[9] maintains a station on Cache Slough at Ryer Island that records tidally filtered daily average flow rates that capture the flow from the Yolo Bypass. The cache slough tidally filtered daily average flow rates are plotted against the paired Freeport daily average flow rates in Figure 21. From visual inspection of the Figure, when the Freeport flow rate is less than approximately 30,000 cfs, the flows at Ryer Island are slough-like reflecting water generally moving back and forth through the system. However, as the flow rate at Freeport increases to over 60,000 cfs, indicating increased storm flows and associated reservoir releases, the flow at Ryer Island increases reflecting the transport of water through the Yolo Bypass to the lower stretch of the Sacramento River. Which is the proper function of the

[8] http://waterdata.usgs.gov/nwis/uv?site_no=11455420
[9] http://waterdata.usgs.gov/nwis/nwisman/?site_no=11455350&agency_cd=USGS

system to begin diverting water to the Yolo Bypass above the City of Sacramento for flood protection as the river flow rates increase.

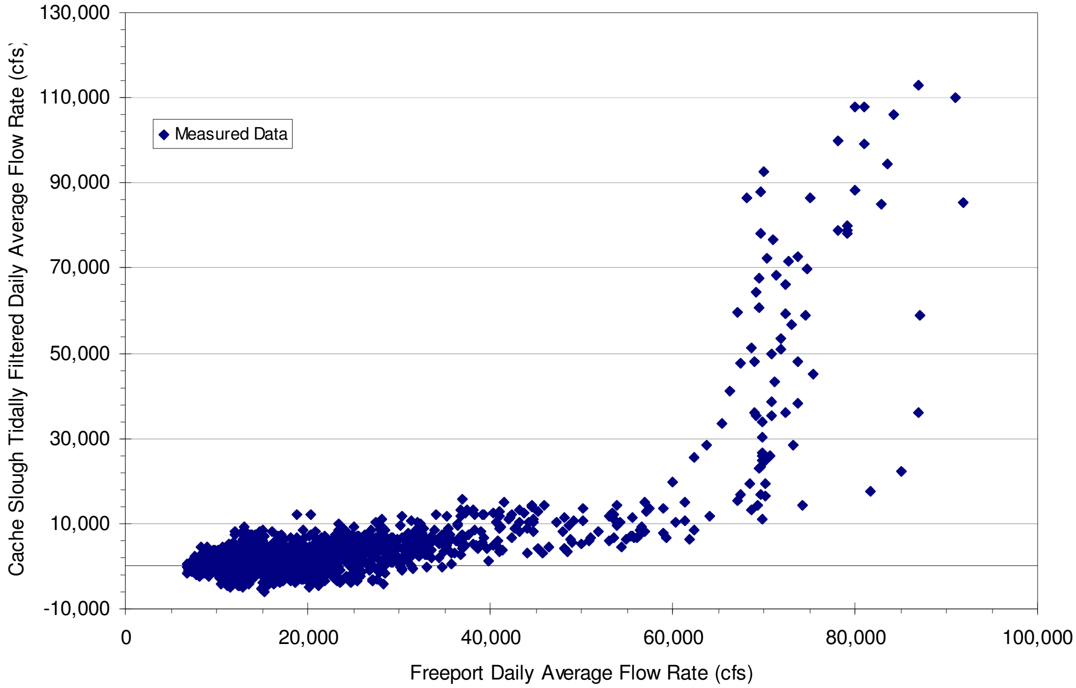


Figure 21: Tidally Filtered Daily Flow Rate Through Cache Slough Compared to the Daily Average Flow Rate in the Sacramento River at Freeport.

To determine a relationship between Freeport flow rate and water velocity downstream of Isleton, the daily averaged velocity at Rio Vista is plotted against Freeport flow rate in Figure 22. A regression analysis performed for the dataset limited to data pairs with Freeport flow rate less than 60,000 cfs yields Equation (5).

$$\begin{aligned} v_{RioVista} &= 0.00001060 \cdot Q_{Freeport} \\ r^2 &= 0.785 \end{aligned} \tag{5}$$

Paired Freeport daily averaged flow rate and Rio Vista daily averaged velocity from December 1998 through January 2010 are plotted in Figure 22 with the LDOPA calculated velocity from Equation (5). The LDOPA model underestimates the velocity at Rio Vista during periods of high flow, however the slower velocity is a conservative measure in the model as the slower velocity will lead to longer residence times with more potential for reactions to increase the dissolved oxygen deficit.

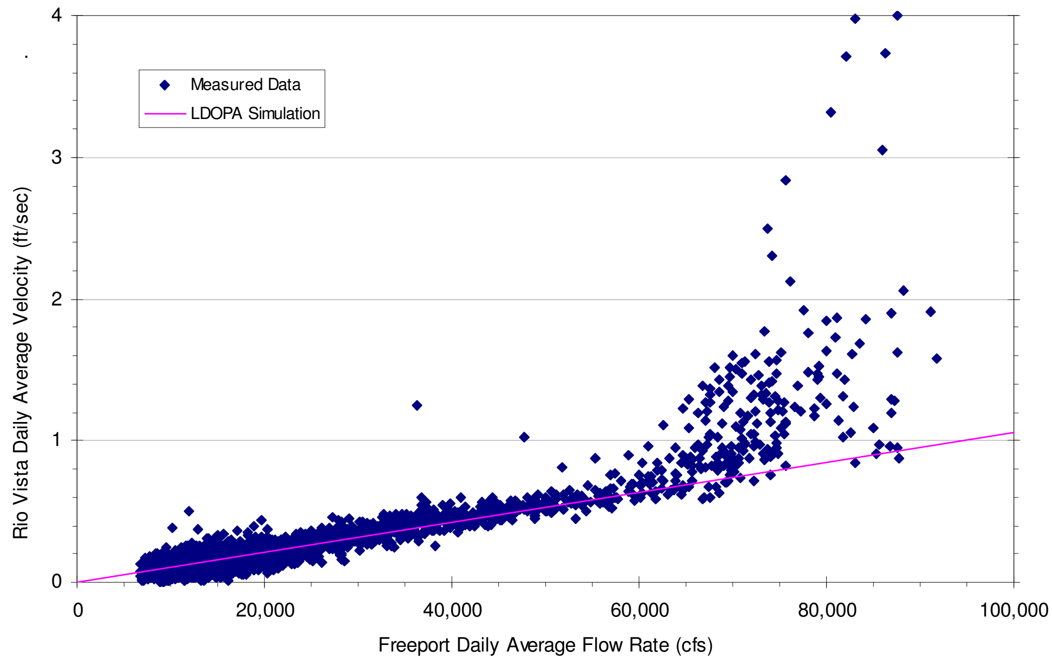


Figure 22: Daily Average Water Velocity at Rio Vista Compared to Daily Average Flow Rate at Freeport.

Temperature

Temperature affects both the saturation concentration of oxygen and the rate coefficients in the LDOPA model.

Sacramento River Temperature

Daily averaged temperature data from the SRCSD DYNTOX input (SRCSD 2009) from Water Year 1922 through 1991 are presented in Figure 23. Generally, the winter temperatures are in the range of 5 to 10 ºC, and summer temperatures range from 20 to 25 ºC. Temperatures used as input to the model for the DO analysis were developed over the 70-year period of record from PROSIM monthly average modeled values disaggregated to hourly temperature values with the Fischer Delta Model (FDM). The PROSIM and FDM are described in SRCSD 2009. Hourly values of temperature are used to calculate the hourly reaeration rates. The daily average river temperature is used for calculating downstream conditions in the Streeter-Phelps model.

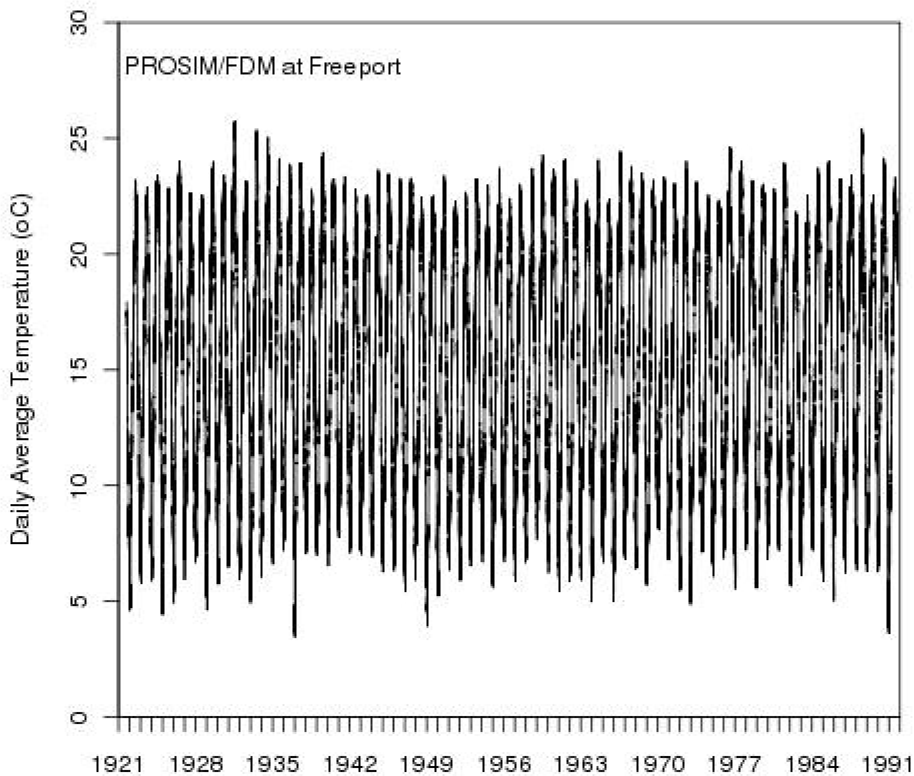


Figure 23: PROSIM/FDM Calculated Sacramento River Daily Average Temperatures at Freeport for the Period of Record Water Year 1922 through 1991.

Dissolved Oxygen

Oxygen Saturation Concentration

Gasses dissolved in water seek equilibrium with the gas present in the atmosphere. As with all gasses dissolved in the water column, the saturation concentration of DO is largely a function of oxygen in the atmosphere, water temperature, atmospheric pressure, and salinity. For freshwater (i.e. salinity under several parts per thousand), the DO saturation concentration is almost exclusively a function of water temperature. The oxygen saturation curve as a function of water temperature is presented in Figure 24 (Tchobanoglous and Schroeder, 1985). For the DO model, the oxygen saturation concentration is determined by the polynomial regression equation determined from the table listed in Tchobanoglous and Schroeder (1985) corresponding to standard atmospheric pressure. The regression is superimposed on the table values in Figure 24. For water temperatures near 5 ºC the saturation concentration for dissolved oxygen increases to over 12 mg/L, however as water temperature nears 25 ºC the saturation concentration drops to near 8 mg/L.

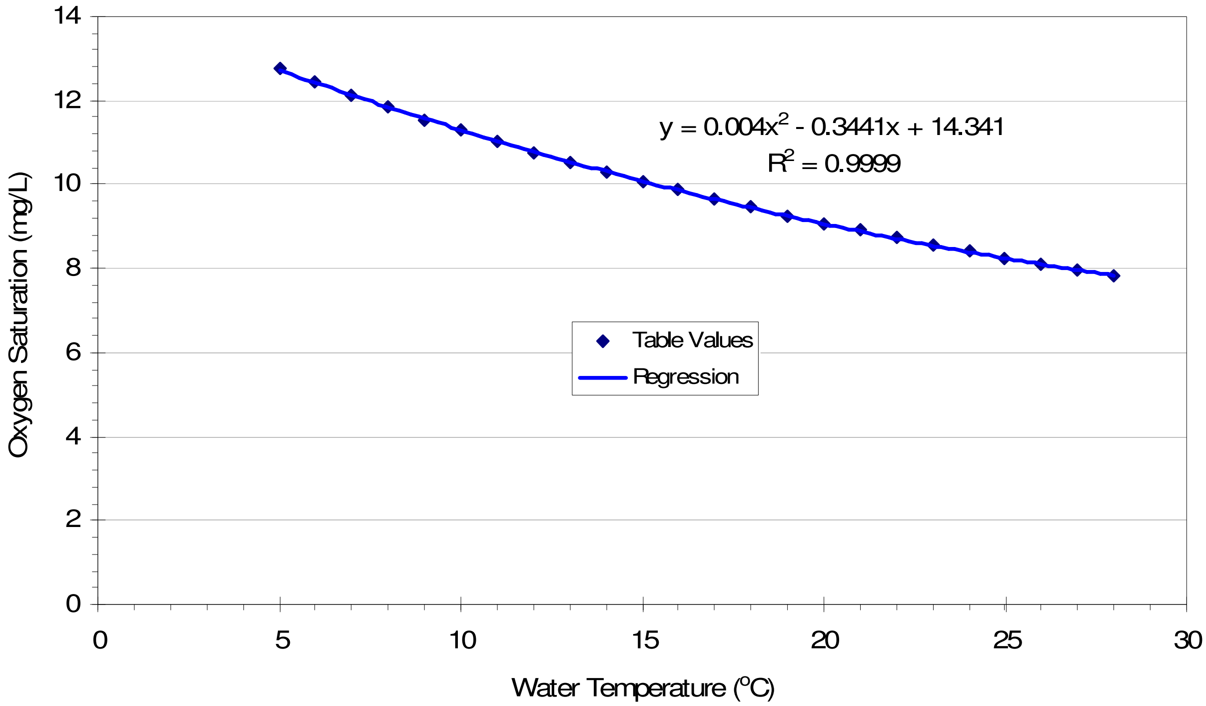


Figure 24: Oxygen Saturation in Water for Standard Atmospheric Pressure.

Sacramento River Dissolved Oxygen

The dissolved oxygen in the Sacramento River at Freeport is generally super-saturated in spring and summer; and near-saturated or slightly below saturated in the fall and winter. Data collected by SRCSD is plotted in Figure 25, note that between 2004 and 2009 the data were recorded to 2 significant figures resulting the integer display of dissolved oxygen above 9.5 mg/L. The SRCSD, CMP, and USGS dissolved oxygen data available for Freeport from 2007-2010 are plotted on Figure 26 with the oxygen saturation concentration. In the model the upstream river dissolved oxygen concentration is set equal to the saturation concentration determined from the upstream river temperature. Currently, the SRCSD is performing a review of available dissolved oxygen data in the Sacramento river and the methods necessary to collect high quality dissolved oxygen data. Additionally, using techniques outlined by the USGS, SRCSD is performing continuous dissolved oxygen monitoring at Freeport, Hood, Walnut Grove, Isleton, and Rio Vista (see Figure 1, for locations).

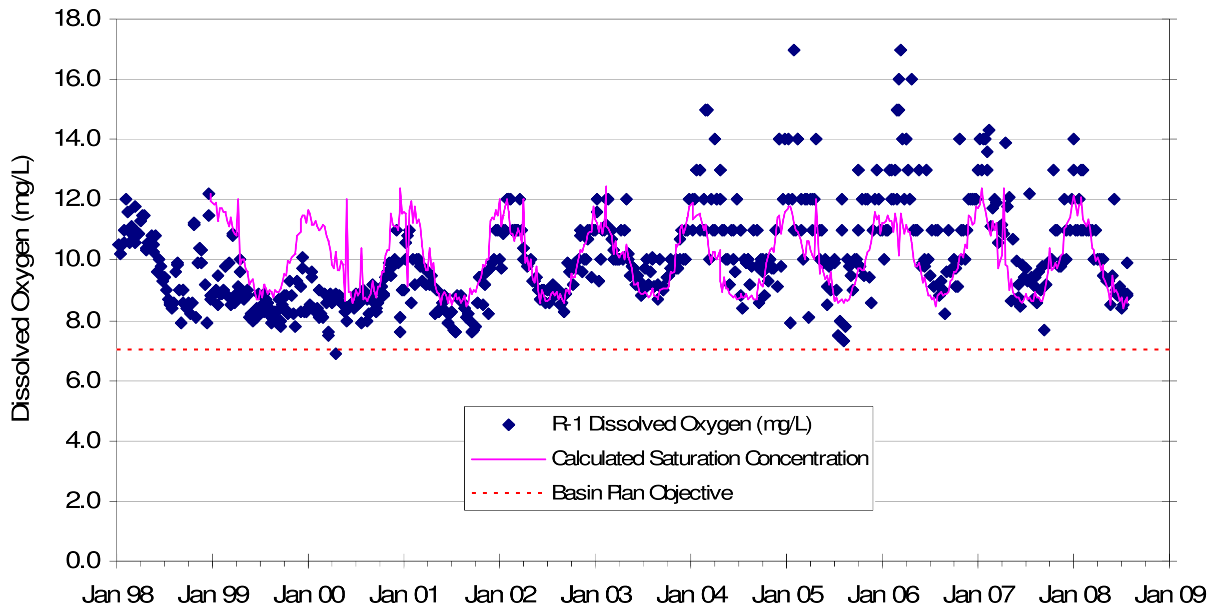


Figure 25: Dissolved Oxygen in the Sacramento River at Freeport (R-1).

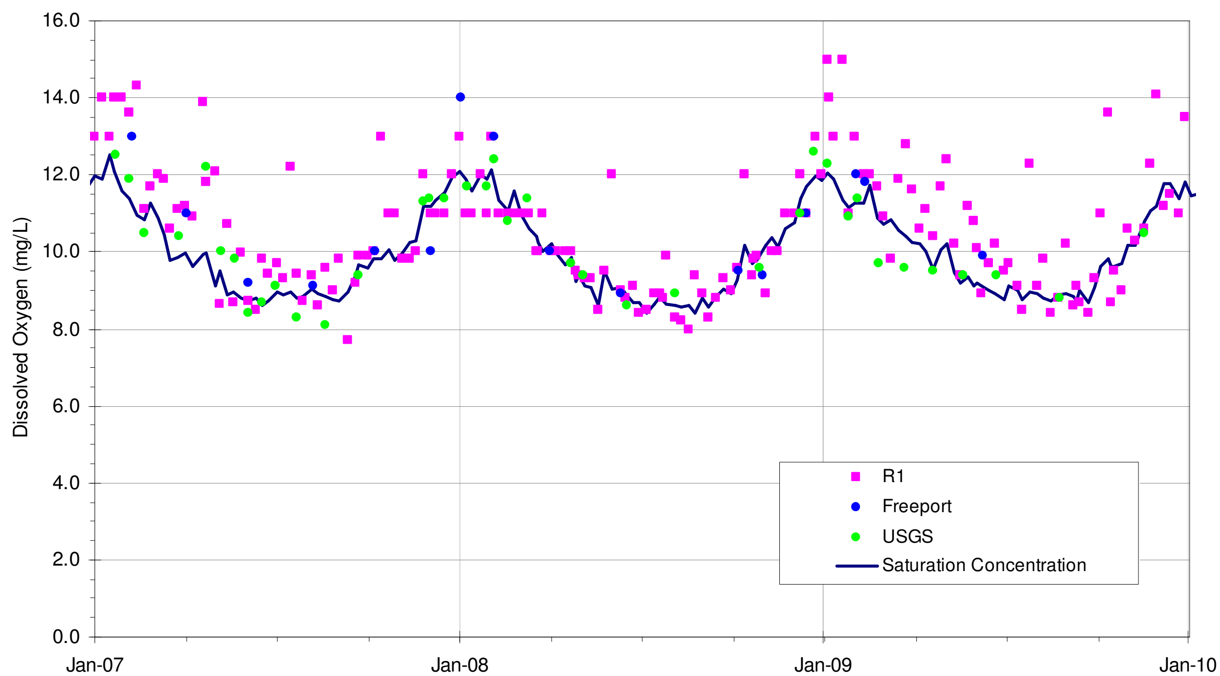


Figure 26: Dissolved Oxygen in the Sacramento River at Freeport 2007-2010.

Oxygen Reaeration Rate

The saturation concentration of oxygen in the water column is the concentration that is in equilibrium with the atmosphere. The difference between the saturation concentration and water column concentration of oxygen is the driving force to draw oxygen to or from the water column depending if there is a deficit or surplus of oxygen in the water column, respectively. The rate of oxygen transfer across the air-water interface is generally thought of as a two-film process to determine an effective surface transfer coefficient (k_L). Typically, for environmental applications the depth scale of the water column is combined into the transfer coefficient to define a reaeration coefficient ($k_2 = k_L/H$, where H is the appropriate depth scale).

Various formulations for k_2 in rivers based on hydraulic parameters such as depth and velocity are available in the literature. As different formulations are developed from specific river systems, the formulas are most valid over specific ranges from which they were developed (USEPA 1985). A review of available relationships is presented in USEPA 1985, with the ranges of applicability for select relationships presented in Figure 27.

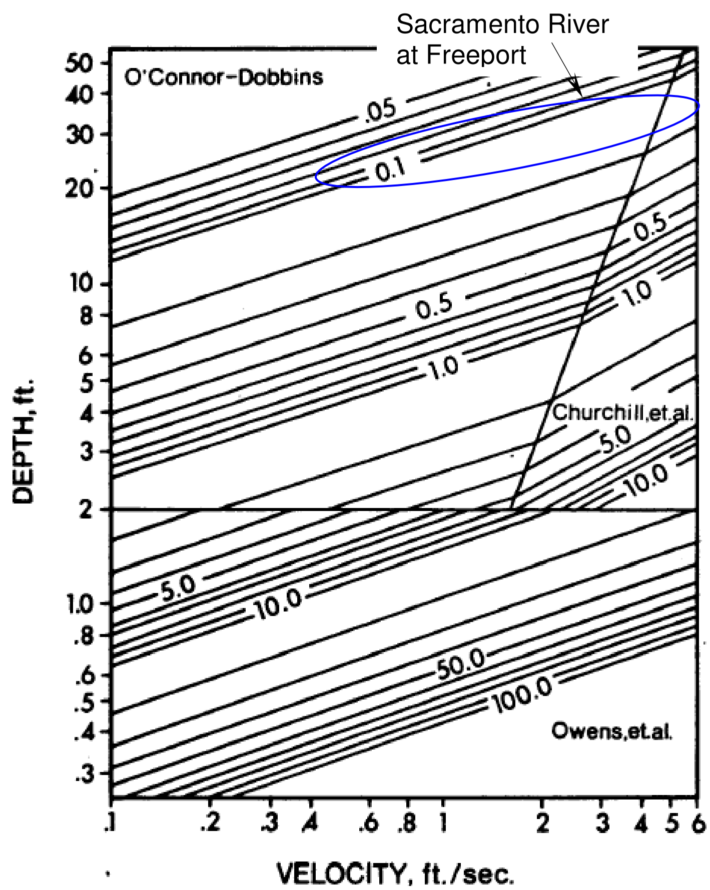


Figure 27: Reaeration coefficient values and applicable relationships for depths and velocities of rivers using methodology of Covar (1976). (USEPA 1985)

Sacramento River Freeport to Isleton

The Sacramento River downstream of the Freeport Bridge is typically greater than 20 feet deep with a water velocities ranging from approximately 0.5 feet/sec to over 4 feet/sec. The area corresponding to the Sacramento River is called out on Figure 27.

For the Sacramento River downstream of the Freeport Bridge, the O'Conner-Dobbins relationship is the most applicable and is presented as Equation (6).

$$k_{2(20)} = \frac{12.9 \cdot u^{0.5}}{d^{1.5}} \tag{6}$$

Where u is the velocity in feet/sec, and d is the depth in feet to calculate the reaeration coefficient at 20 ºC in 1/day.

Note that the portion of Figure 27 that corresponds to Churchill, et al., occurs at high river flow rates and would result in a greater reaeration rate. Therefore, it is a more conservative approach to use Equation (6) for all flows. As a conservative modeling approach the wind induced reaeration is not considered in the section of river between Freeport and Isleton.

The temperature dependence of the reaeration rate is determined via Equation (7) with the Arrhenius coefficient selected from USEPA, 1985. Equations (2) and (4) are utilized to determine the depth and velocity of the river as a function of flow rate.

$$k_2 = k_{2(20)} \cdot 1.024^{T-20} \tag{7}$$

Where T is the water temperature in °C.

Sacramento River Downstream of Rio Vista

In the vicinity of Rio Vista, the Sacramento River widens significantly and the water depth nearly doubles. Downstream of Rio Vista the river is much more estuary-like than river-like. Additionally, the Carquinez Straits downstream from Rio Vista act to funnel wind from the generally cooler San Francisco Bay up to the generally warmer Central Valley and provide consistent, strong winds in the estuary-like portion of the Sacramento River. To capture the reaeration that occurs in the estuary-like portion of the Sacramento River the wind induced reaeration described in USEPA 1985 is added to Equation (7) resulting in Equation (8). (7) or (8)

$$k_2 = \left(0.2395 \cdot v_W^{1.643} + 1.0\right) \cdot \frac{12.9 \cdot u^{0.5}}{d^{1.5}} \cdot 1.024^{T-20} \tag{8}$$

Where v_W is the wind speed in meters/sec.

Hourly data for wind velocity, water velocity, water depth, and water temperature are used to calculate hourly values for k_2 using Equation (8). The hourly k_2 were averaged to daily values and log-normal distributions for each day of the year were calculated. Wind speed data were obtained from the RVB station[10] CDEC database and were cleaned to remove negative values, extreme high values, and corrected to required units of meters/sec. Data obtained from USGS for the station Sacramento River at Rio Vista (11455420) were used for the hourly water velocity and depth. The USGS velocity and stage data required correction as the datum was adjusted[11] October 2005. In the vicinity of Rio Vista the mean water level (MWL) of the Sacramento River is 10.1 meters (33.1 feet)[12]. Utilizing the USGS gauge station for tidal elevation change the record of water depth may be determined. The water temperature data available from the Rio Vista station begins in 2008, to provide a longer period of record the water temperatures recorded for the Sacramento River at Hood[13] are used to calculate the reaeration rate. Each data

[10] http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=rvb
[11] Jon R Yokomizo [jryoko@usgs.gov], email com. April 14, 2010
[12] http://sfbay.wr.usgs.gov/access/wqdata/overview/wherewhen/where.html
[13] http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=srh

set was reviewed for consistency and inconsistent data removed. The available hourly data from each data set used to calculate the reaeration rate are presented as time series in Figure 28. A two year period time series of the wind speed at Rio Vista is presented in Figure 29 to illustrate the typical pattern of high summer winds with lower winter winds. Where paired data existed for all four data sets, the hourly reaeration rate was calculated and the resulting time series of data is displayed in Figure 30. The daily averaged k_2 values are superimposed on the hourly values in the Figure.

For use in the LDOPA model, the daily average k_2 are combined by their respective day of year (DOY) to develop a log-normal distribution for each DOY. The average and 90th percentile values from the developed distributions are superimposed on the daily averaged values in Figure 31. When developing the distributions, any k_2 greater than 1.2 per day were excluded as they were likely an outcome of extreme high wind conditions not necessarily reflective of expected conditions. Limiting the k_2 values to 1.2 per day is a conservative measure.

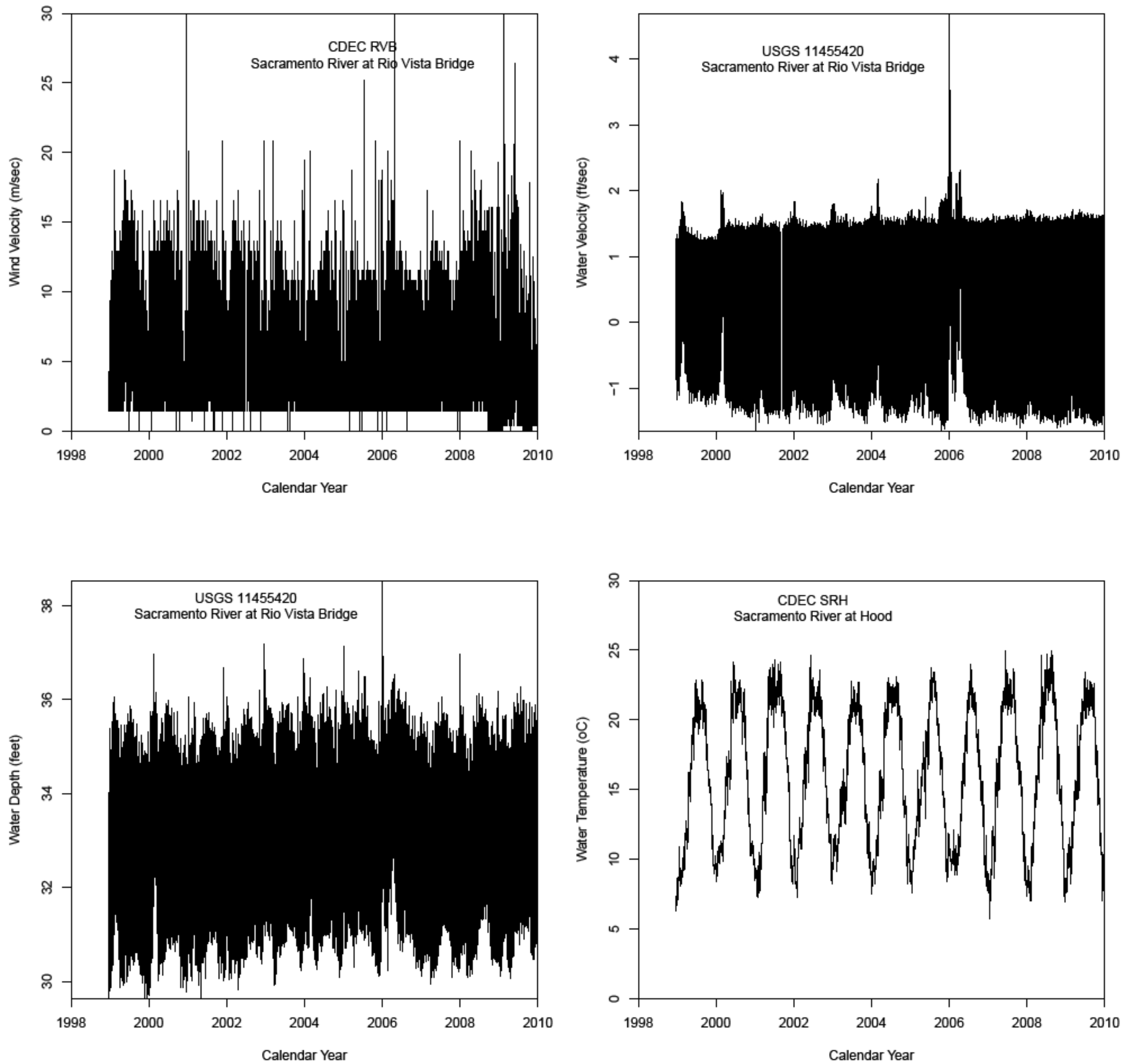


Figure 28: Hourly Data Used in Calculation of Reaeration Rate Downstream of Isleton.

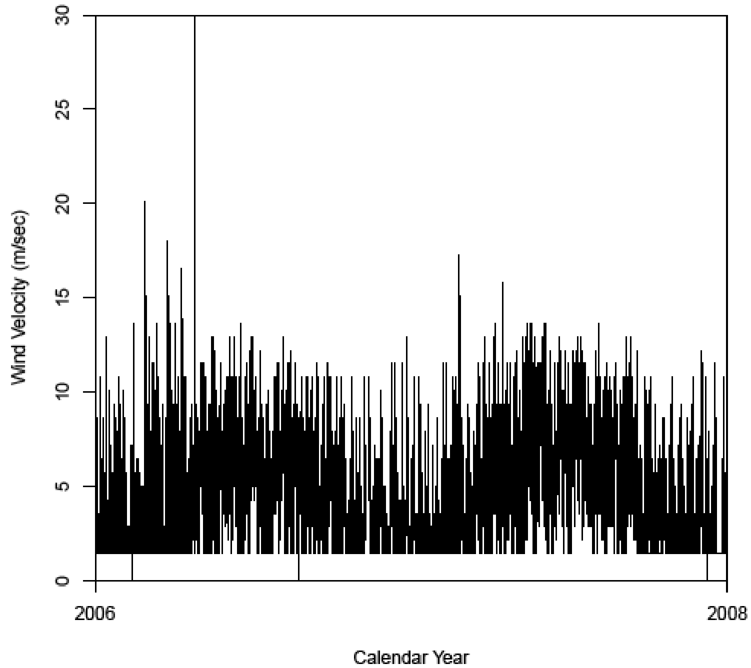


Figure 29: Time Series of Wind Speed Measured at Rio Vista over Two Year Period.

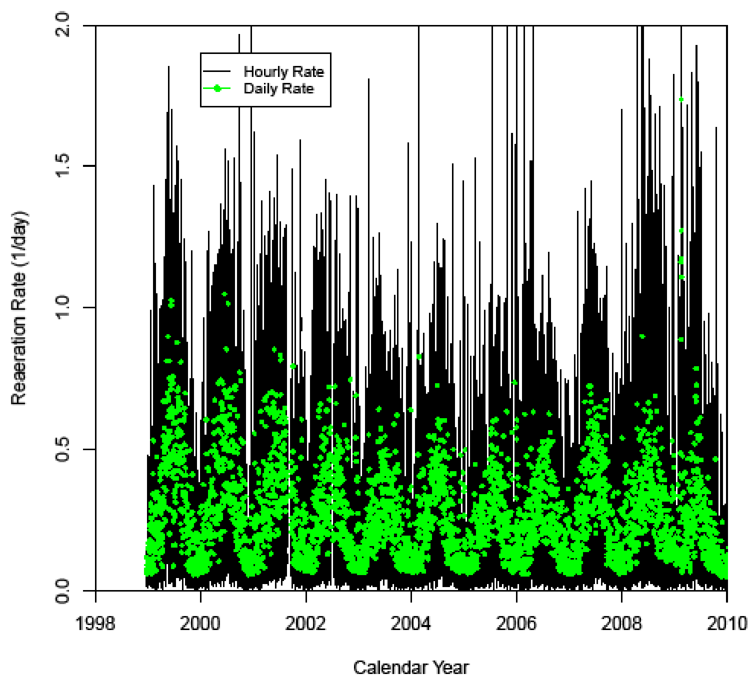


Figure 30: Calculated Hourly and Daily Average Reaeration Rates for the Sacramento River Downstream of Isleton.

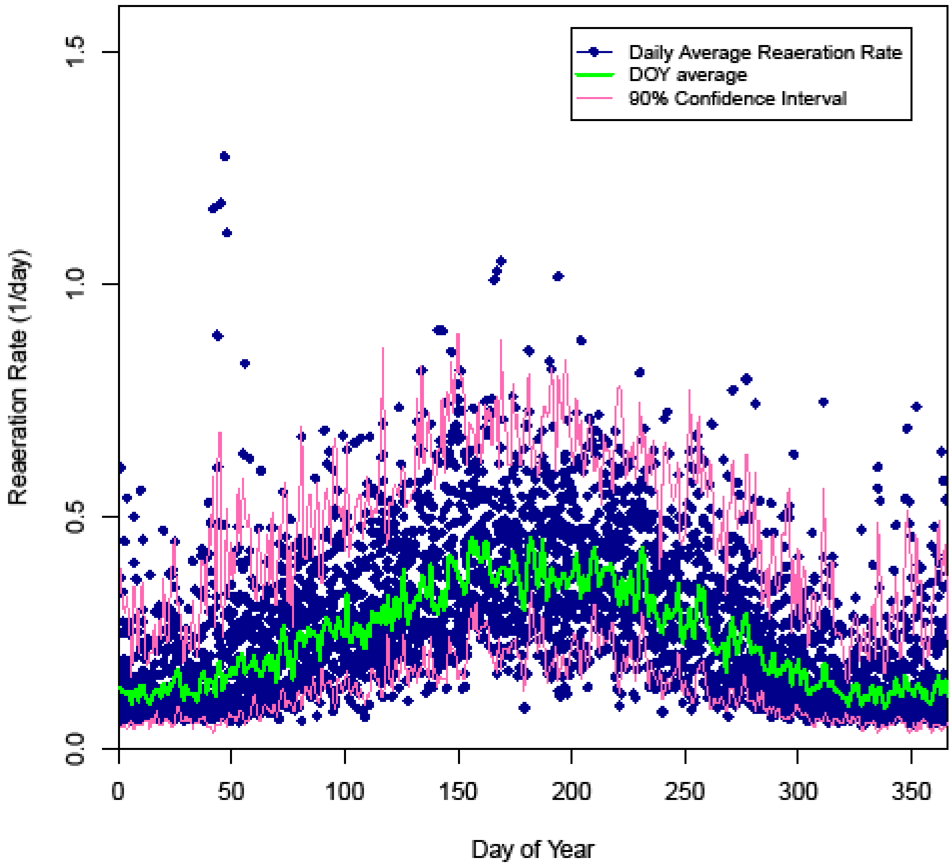


Figure 31: Reaeration Rates for the Sacramento River Downstream of Isleton Plotted by Day of Year (DOY). Modeled Average and 90th Percentile for the DOY as Utilized in the LDOPA Model.

Carbonaceous Biochemical Oxygen Demand

Respiration of organic materials consumes oxygen. The typical measurement of the oxygen demand is the 5-day biochemical oxygen demand (BOD_5). The ultimate demand for oxygen to completely oxidize the materials present is typically 1.5 times the BOD_5 (Tchobanoglous and Schroeder 1985). In the Streeter-Phelps approach, degradation of the oxygen demanding constituents is modeled as a first-order reaction. Furthermore, the LDOPA model splits the CBOD into dissolved and particle associated fractions. The dissolved carbonaceous oxygen demand is treated as follows: $L_{db} = L_{db_i} e^{-k_{db}\Theta_H}$. The particulate carbonaceous oxygen demanding substances are allowed to be degraded (k_{pd}) and settled (k_s) from the water column for an effective first-order degradation rate of $k_r = k_{pb} + k_s$, to yield: $L_{pb} = L_{pb_i} e^{-k_r\Theta_H}$. Generally, the settling rate can be approximated by dividing the settling velocity (v_s) of the particles by the water depth (D), $k_s = {}^{v_s}\!/_{D}$ (USEPA 1990). The CBOD is assumed to be 20% particulate for the Sacramento River system. Due to the low levels of carbonaceous BOD in the system, the fraction of particulate BOD does not significantly affect the DO model.

Sacramento River Biochemical Oxygen Demand

Measurements of the CBOD upstream of the discharge are not available. A normal distribution with an average of 0.3 mg/L and standard deviation of 0.05 mg/L is assumed for the upstream CBOD concentrations in the Sacramento River.

Nitrogenous Biochemical Oxygen Demand

Nitrification is the oxidation of ammonia nitrogen through intermediary steps to nitrate. Additionally, organic nitrogen may be degraded to ammonia via ammonification. The stoichiometry of the processes results in 4.56 oxygen mass consumed for each mass as N of ammonia nitrified (Tchobanoglous and Schroeder 1985). The nitrogen oxygen demand may be written as: $L_{nh_3} = L_{nh_{3i}} e^{-k_{nh_3}\Theta_H} + \frac{O_2}{N}\frac{k_{OrgN}\cdot OrgN_i \cdot}{\left(k_{nh_3} - k_{OrgN}\right)}\left(e^{-k_{OrgN}\Theta_H} - e^{-k_{nh_3}\Theta_H}\right)$. Appendix B contains the details regarding the derivation of the nitrogen oxygen demand considering both ammonification and nitrification.

Sacramento River Ammonia Concentrations

The measured ammonia data from the Sacramento River at Freeport are plotted in Figure 32. The 219 sample dataset only contains 14 detected values of ammonia in the river upstream of the discharge. Available data from SRCSD indicate approximately 6% of ammonia samples exceed 0.1 mg/L as N.

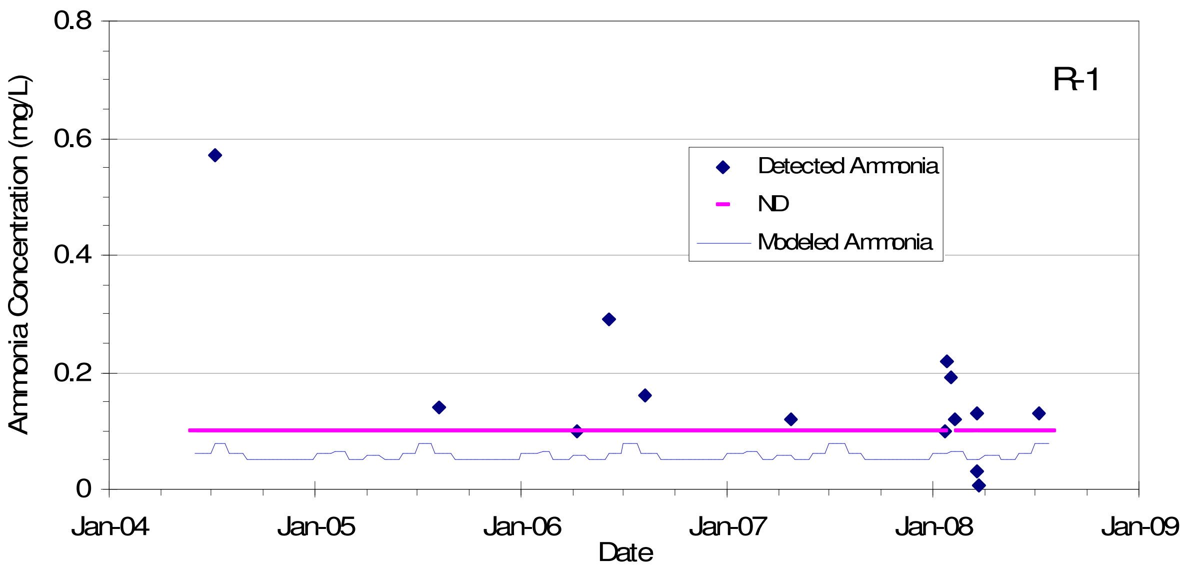


Figure 32: Measured Ammonia in Sacramento River at Freeport. The Dataset is Comprised of 14 Detected Values and 205 Non-Detected Values.

USGS performs water quality measurements at Freeport[14]. A plot of available ammonia and organic nitrogen data at the corresponding river flow rate are plotted in Figure 33. Neither organic nitrogen or ammonia appear to display a relationship with river flowrate. Ammonia data

[14] http://nwis.waterdata.usgs.gov/ca/nwis/qwdata/?site_no=11447650&agency_cd=USGS

are presented as a log-normal distribution in Figure 34 and reflect the modeled values in the LDOPA model. The probability distribution for the USGS ammonia data at Freeport can be used to estimate approximately 15% of ammonia data are greater than 0.1 mg/L as N and so using the USGS ammonia data is a more conservative estimate of the river concentrations because the SRCSD dataset contains approximately 6% greater than 0.1 mg/L as N. The USGS data are sampled less frequently but encompass a broader time frame than the SRCSD dataset.

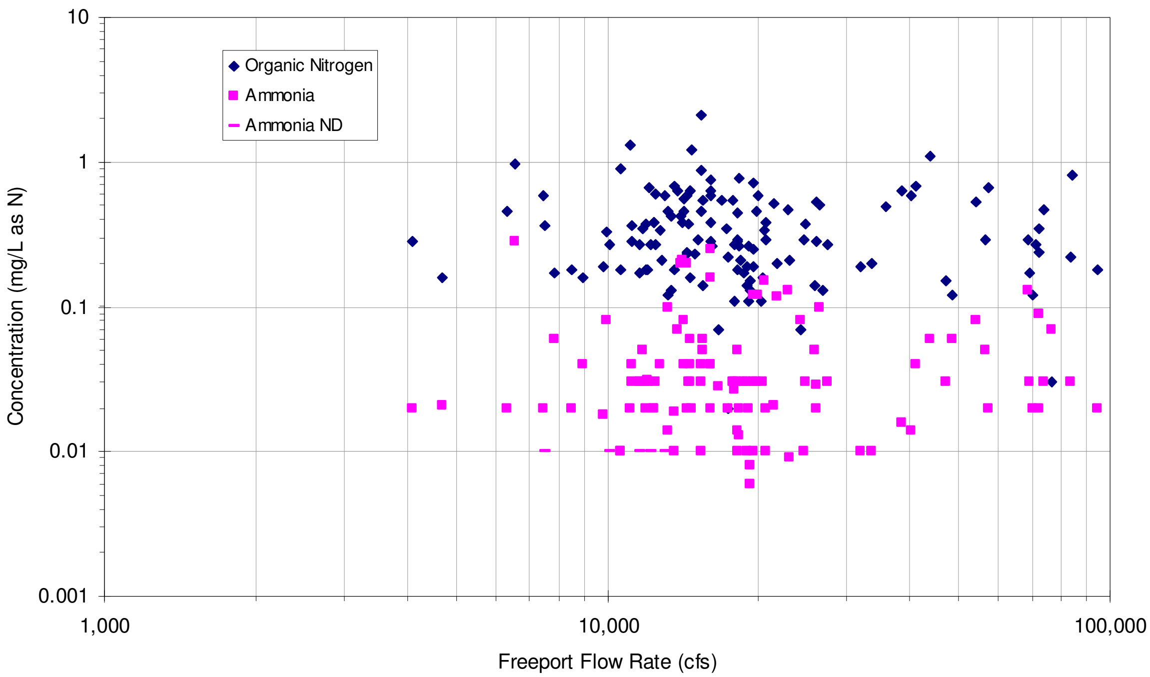


Figure 33: USGS Organic Nitrogen and Ammonia Data at the Corresponding River Flow Rate.

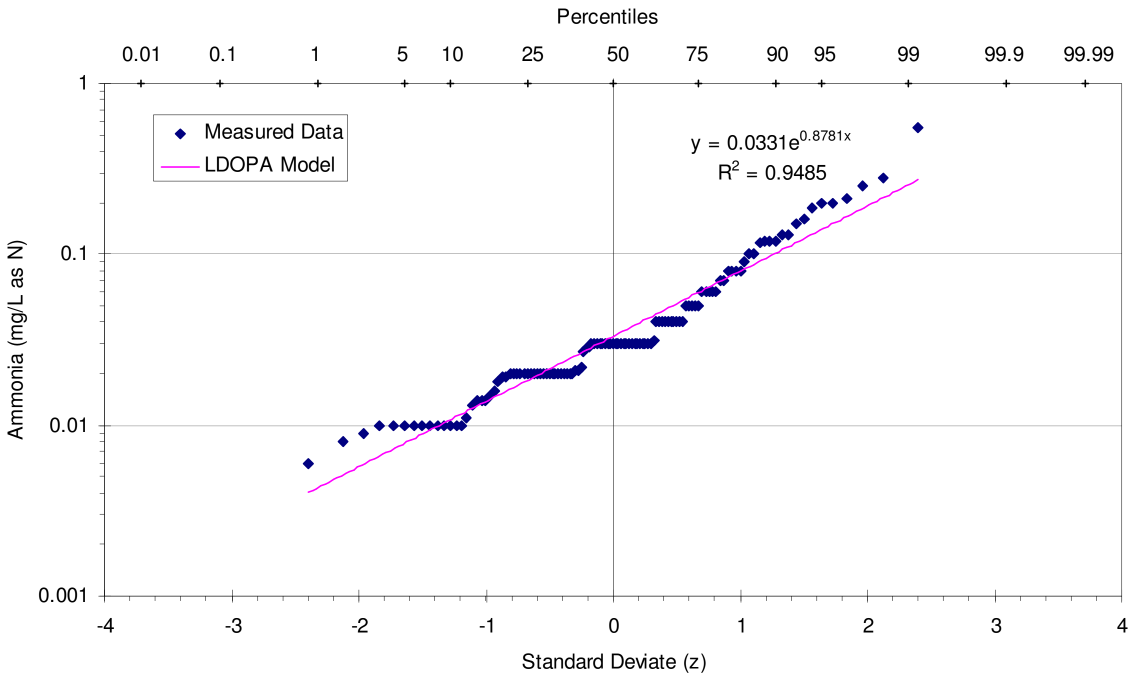


Figure 34: USGS Ammonia Data for Sacramento River at Freeport.

Sacramento River Organic Nitrogen Concentrations

Organic nitrogen is routinely measured by USGS at the Freeport monitoring station. The log-normal distribution of organic nitrogen in the Sacramento River at Freeport is presented in Figure 37. As there is no relationship with flow as demonstrated in Figure 33, the LDOPA model uses the log-normal distribution displayed in Figure 35 as the input organic nitrogen concentrations for the Sacramento River at Freeport.

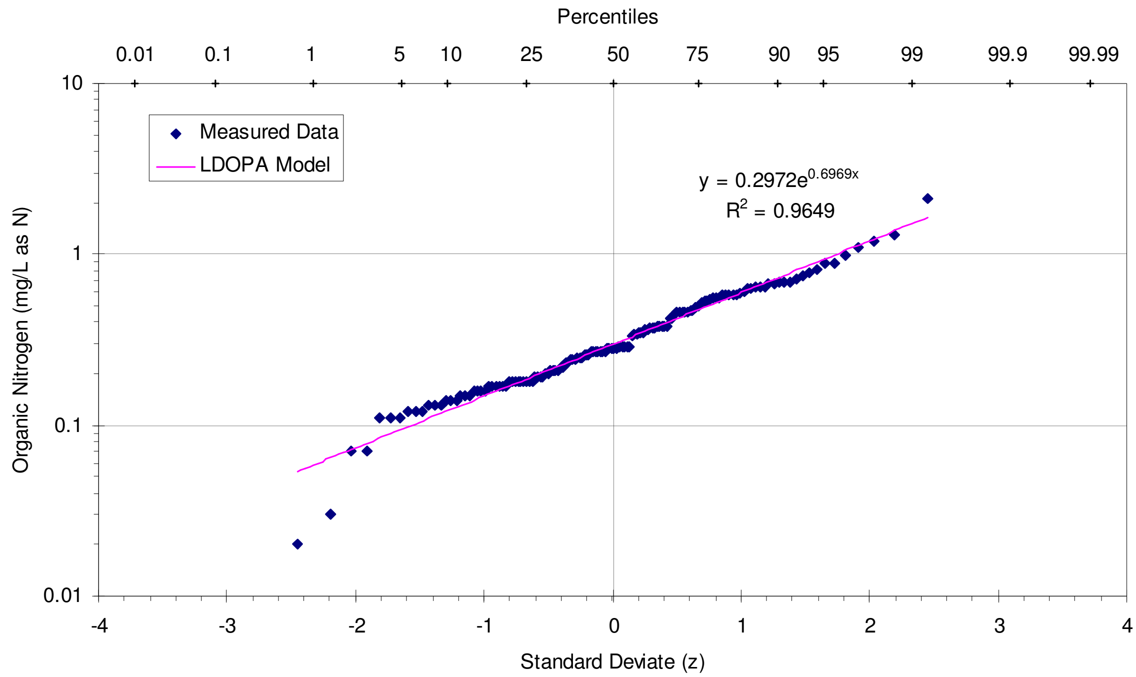


Figure 35: USGS Organic Nitrogen Data in Sacramento River at Freeport.

SRWTP Effluent Flow rates

The measured SRWTP effluent flow rate data over the 23 year period spanning 1985 through 2008 are plotted in Figure 36. Measured effluent flow rates were normalized to the respective annual average flow rate and evaluated by month to determine the relative monthly average. The modeled average monthly flow is calculated as the annual average multiplied by the normalized monthly average. The monthly average flow rates adjusted by the annual average are superimposed on the measured data in Figure 36. Similarly the monthly variability was calculated by determining the ratio of measured flow rate to modeled monthly average and forming the monthly standard deviations. While higher than average flow rates are well represented by a log-normal distribution, the lower than average flows generally are not, with a log-normal distribution greatly underestimating the lower treatment plant flows, to better estimate the lower than average flow rates, a modified log-normal distribution is utilized. Equation (9) lists the function used in the LDOPA model to calculate effluent flow rates, with the monthly parameters listed in Table 7. The modeled flow rates and variability displayed as the 90% confidence interval are superimposed on the paired measured effluent flow rate data in Figure 37.

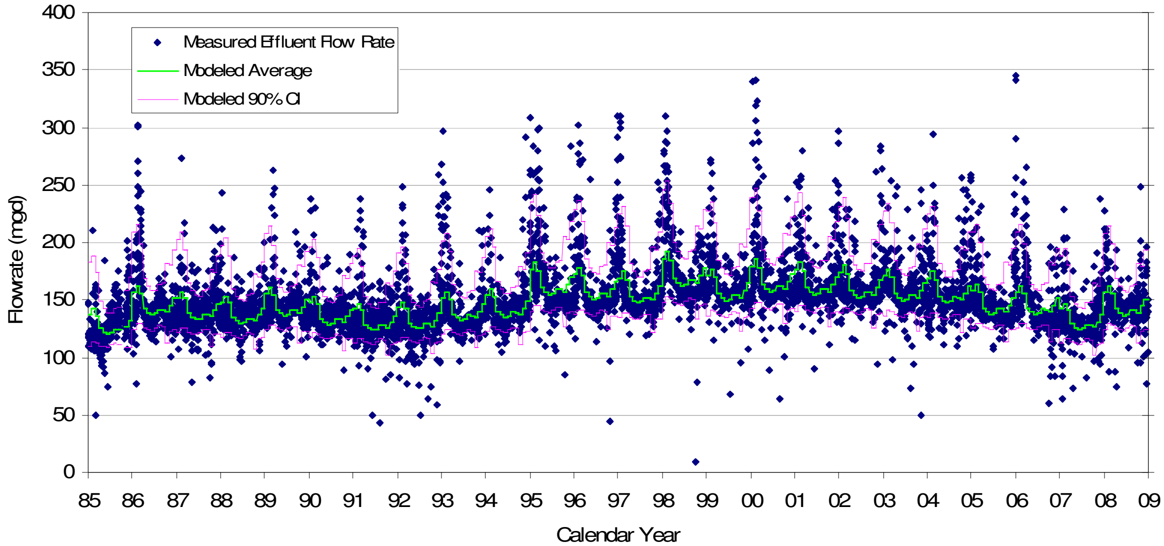


Figure 36: Measured and Modeled SRWTP Effluent Flow Rates.

$$Q_{eff} = Q_{ADWF} \cdot Q_{normave} \begin{cases} \left(1 + z \cdot Q_{cov}\right) & z \geq 0 \\ \left(1 - \sqrt{-z/1.25} \cdot Q_{cov}\right) & z < 0 \end{cases} \tag{9}$$

Table 7: Monthly Parameters Normalized to ADWF Describing SRWTP Effluent Flow Rate.

Month	Normalized Average ($Q_{normave}$)	Normalized COV (Q_{cov})
January	1.1371	0.20036
February	1.1759	0.19860
March	1.1276	0.16847
April	1.0317	0.11432
May	1.0076	0.10204
June	0.9920	0.09571
July	1.0004	0.08556
August	1.0258	0.09259
September	1.0249	0.09710
October	1.0109	0.18531
November	1.0512	0.14569
December	1.0945	0.17258

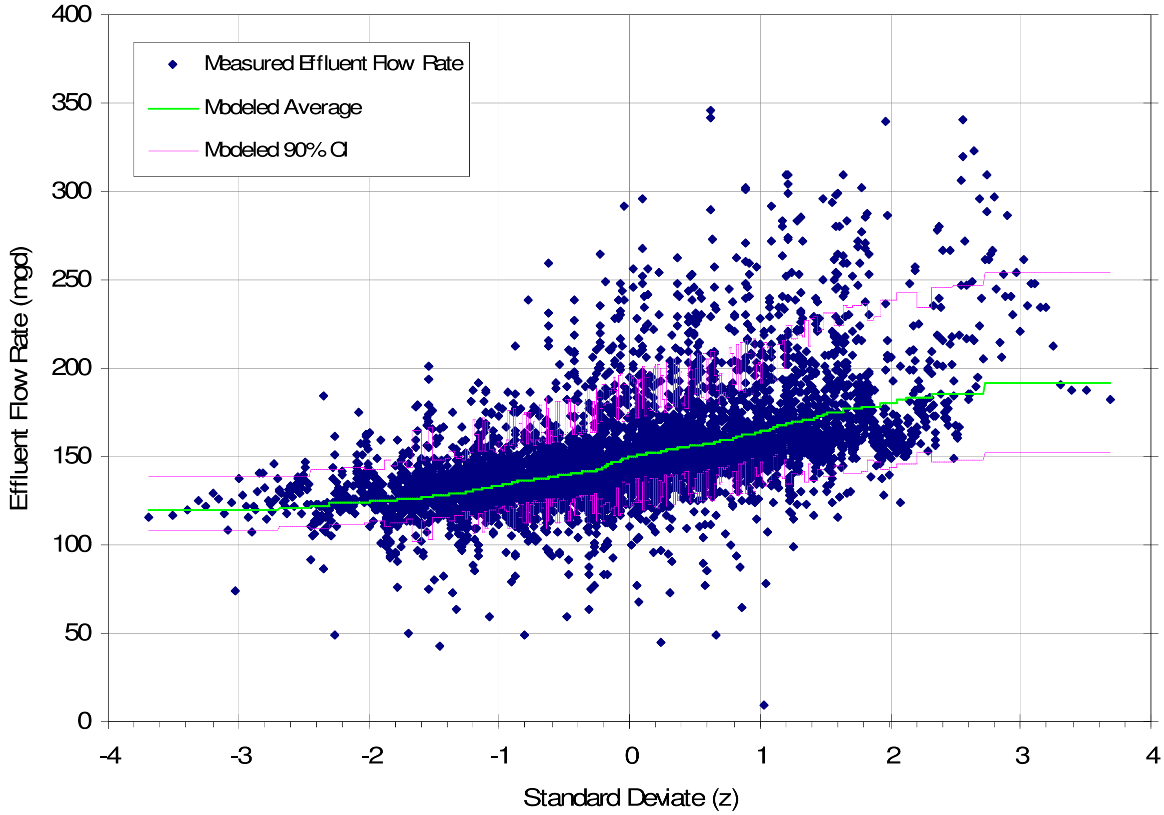


Figure 37: Distribution of Modeled SRWTP Effluent Flow Rate with Paired Measured Flow Rates. Both Modeled Average and Confidence Interval Vary by Month Leading to Jagged Appearance in the Plot.

Current permitted average dry weather flow rate (ADWF) is 181 MGD and the requested permitted ADWF is 218 MGD. In the Streeter-Phelps model, the ADWF effluent flow rate is used to modify the modeled monthly average and variability over a simulation. Dynamic LDOPA model generated effluent flow rates corresponding to 218 mgd ADWF are plotted on Figure 38 along with the modeled monthly average and 90% confidence interval. Measured effluent flow rate data from 1998 through 2009 scaled by the respective annual average to an ADWF of 218 mgd are also plotted in Figure 38 for comparison.

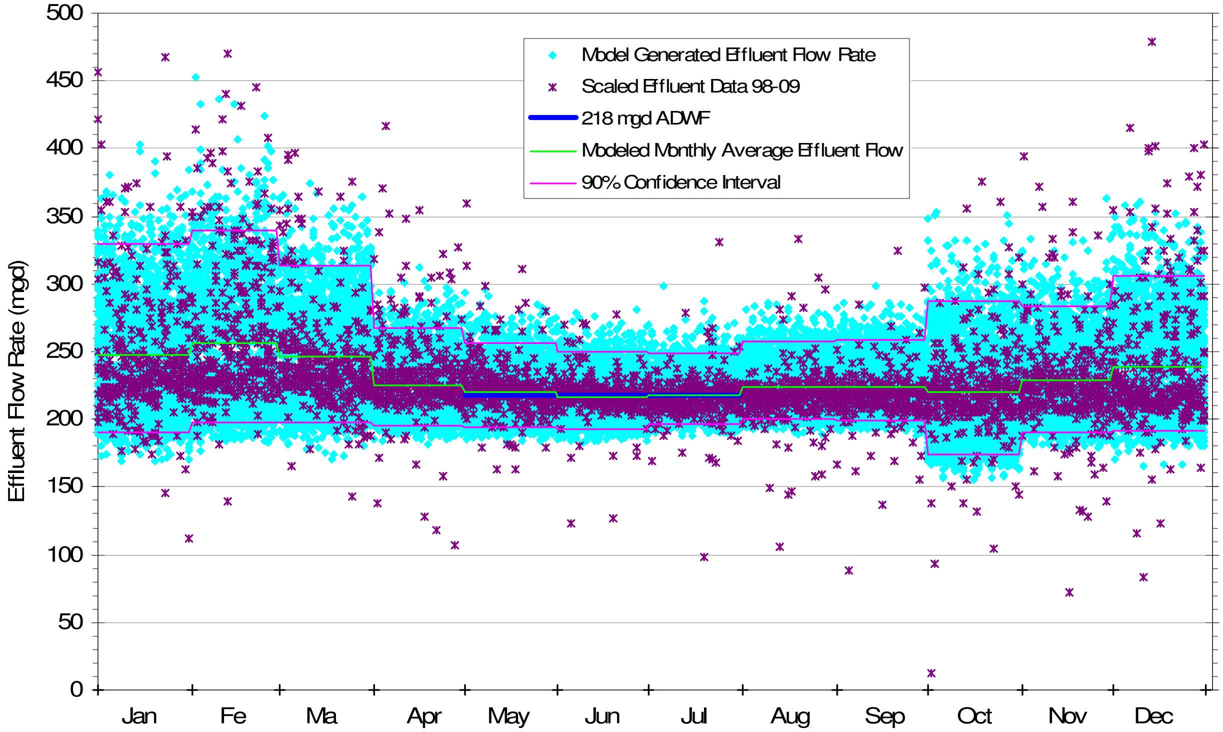


Figure 38: Dynamic LDOPA Model Generated Effluent Flow Rates for 218 mgd ADWF. STWRP Measured Effluent Flow Rate Data Scaled to 218 mgd ADWF.

SRWTP Effluent Temperature

Effluent temperature data measured from June 2004 to June 2008 are plotted in Figure 39 with monthly average temperatures superimposed. Monthly average and standard deviations calculated from the data define the monthly normal distributions used in the Dynamic LDOPA model to calculate effluent temperatures are listed in Table 8. A comparison between the Dynamic LDOPA model generated temperatures and the measured effluent temperatures is presented as Figure 40.

Table 8: Monthly Average and Standard Deviations Corresponding to Monthly Normal Distributions used to Calculate Effluent Temperatures for the Dynamic LDOPA Model.

Month	Average (°C)	Standard Deviation (°C)
January	18.8	1.2403
February	19.4	0.7090
March	20.1	0.9052
April	21.1	1.0900
May	22.9	0.6922
June	24.7	0.7632
July	26.0	0.5489
August	26.5	0.2522
September	26.2	0.5973
October	24.7	0.7923
November	22.9	0.9285
December	20.5	1.0895

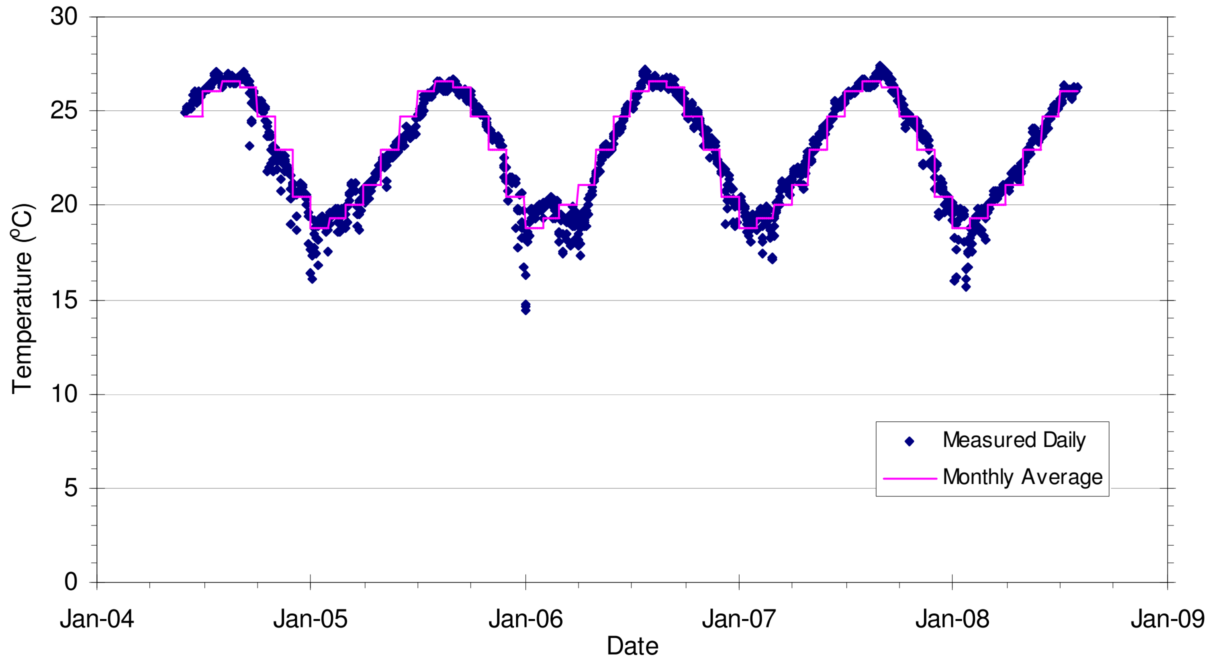


Figure 39: SRWTP Effluent Measured Daily Temperatures and Monthly Average Temperatures.

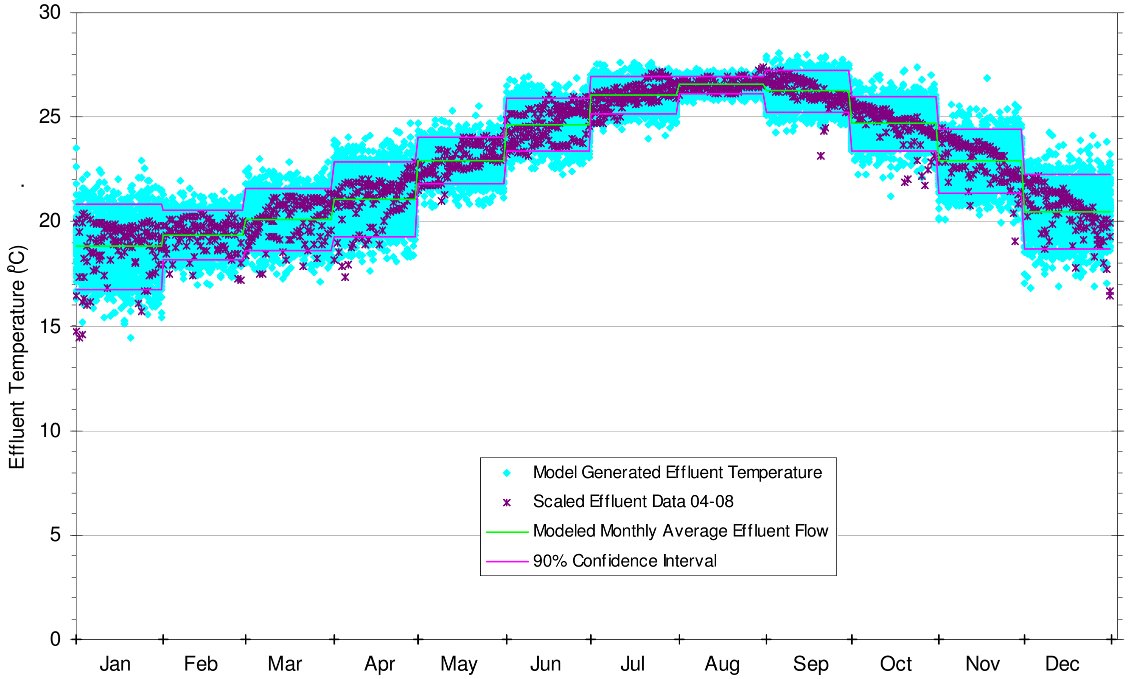


Figure 40: Monthly Effluent Temperature Comparison between Dynamic Model Generated Values and Measured SRWTP Effluent.

SRWTP Effluent Dissolved Oxygen

Dissolved oxygen measurements of the SRWTP effluent are not generally available. Limited measurements of the effluent dissolved oxygen are presented in Figure 41. Because of the relatively high levels of dilution available and the river is typically near or above the saturation concentration, the analysis is not sensitive to the effluent DO concentration.

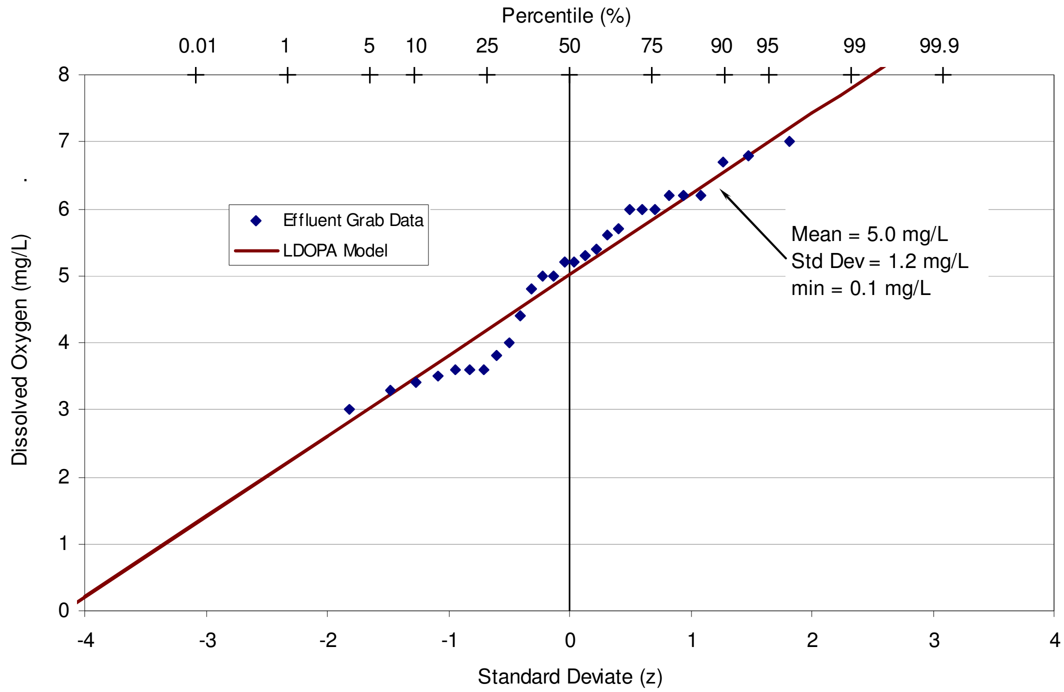


Figure 41: SRWTP Effluent Dissolved Oxygen Concentrations.

Upstream of the outfall the dissolved oxygen in the Sacramento River is generally at saturation. As the SRWTP discharge mixes with the river, the dissolved oxygen concentrations are nearly identical to the upstream concentrations. To assess the change in dissolved oxygen, the ratio of paired data are presented in Figure 42 along with the modeled complete mix dissolved oxygen concentration (DO_i in the Streeter-Phelps model) divided by the upstream dissolved oxygen concentration, which is set to the saturation concentration. Prior to 2003, the ratio is variable but generally slightly less than 1.0, indicating the dissolved oxygen is slightly lower downstream of the SRWTP discharge. Some of the variability observed in the Figure is due to the precision at which the dissolved oxygen can be measured and it is the ratio of two measured values that is plotted. Post 2003, the ratio is generally 1.0 but appears more variable; however, the result is an artifact of the two significant figures recorded.

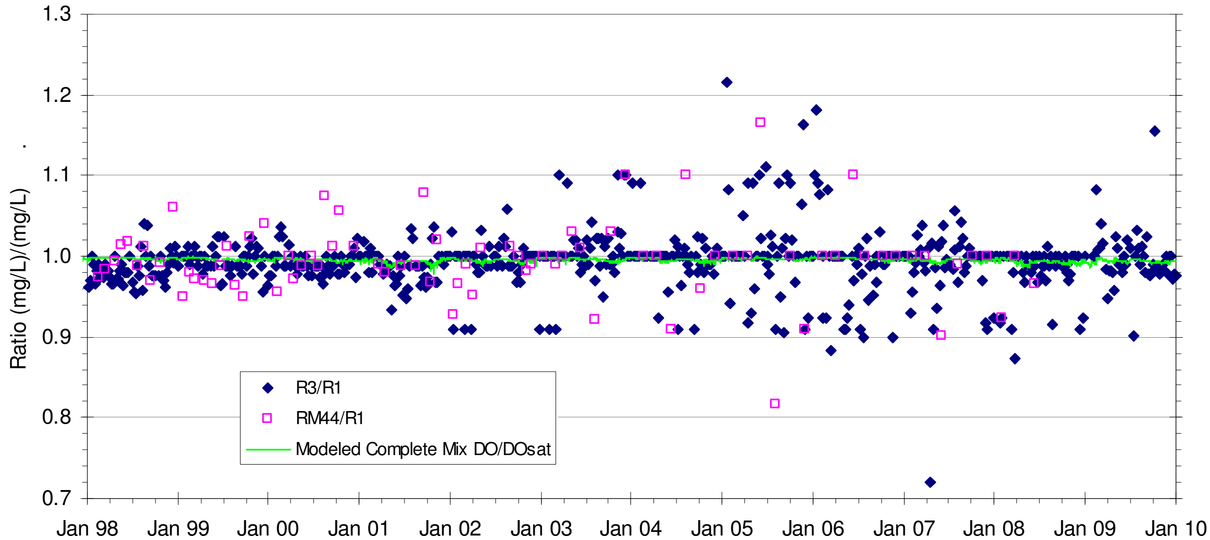


Figure 42: Measured and Modeled Ratio of Upstream to Downstream Dissolved Oxygen Concentrations. Modeled Effluent Dissolved Oxygen Concentration Set to Constant 2.0 mg/L.

SRWTP Effluent Biochemical Oxygen Demand

The available BOD_5 measured in the SRWTP effluent are plotted in Figure 43. Additionally, the average BOD_5 of 7.4 mg/L is denoted on Figure 43. The SRWTP effluent BOD_5 concentrations from June 2004 through March 2010 were used to develop a modified log-normal distribution for use as input to the LDOPA dynamic model. The modified log-normal distribution for SRWTP effluent daily composite BOD_5 measurements is presented in Figure 44. Additionally, the distributions for weekly and monthly average BOD_5 concentrations are plotted on Figure 44. As listed in Equation (10), the developed distribution of daily SRWTP effluent BOD_5 was multiplied by 1.1 to provide a model input condition exceeding the current treatment plant performance by 10%. The ultimate BOD is determined in the model by multiplying BOD_5 by 1.5.

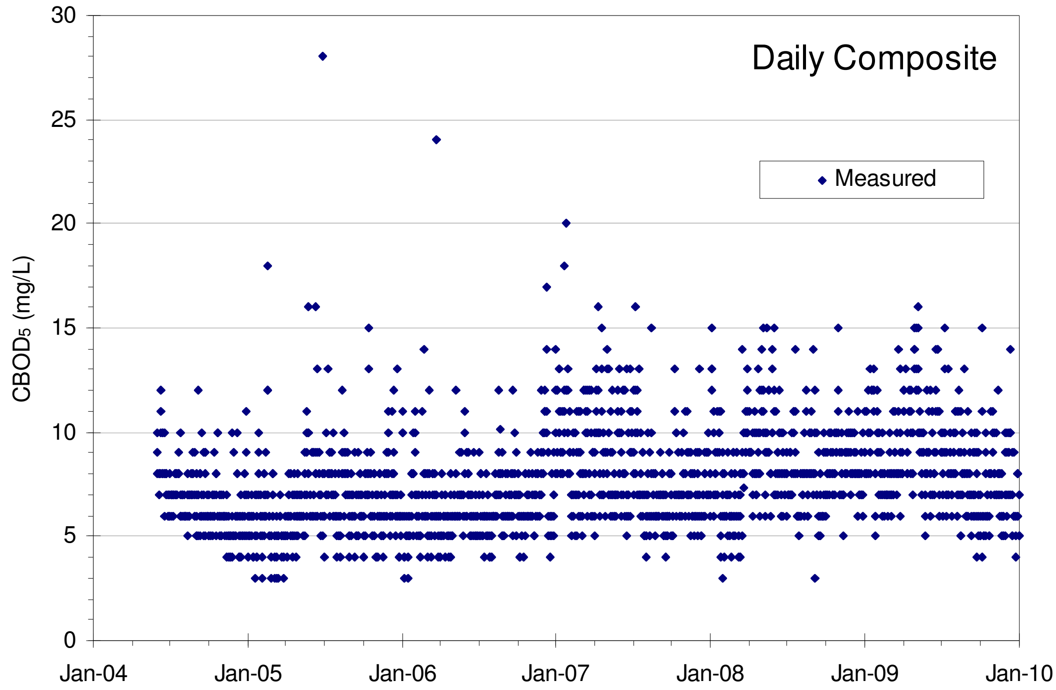


Figure 43: Carbonaceous BOD_5 Measured in SRWTP Effluent.

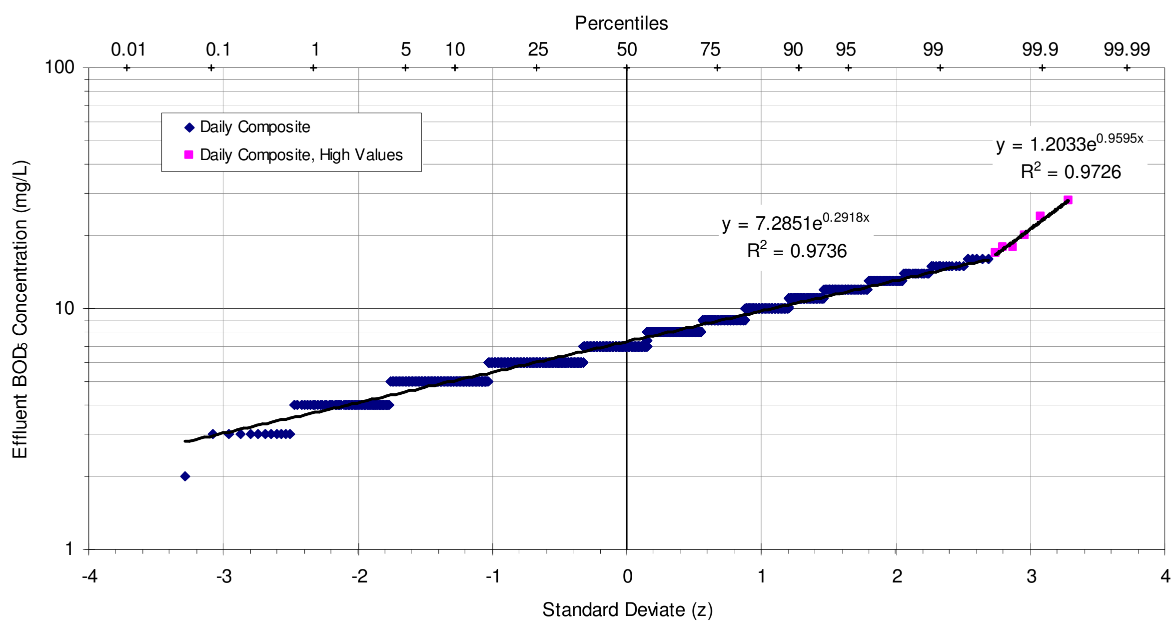


Figure 44: Distribution of SRWTP Effluent BOD_5 Concentrations. Daily Composite, and Weekly and Monthly Average Distributions are Plotted, with Equations Corresponding to Daily Composite Data.

$$BOD_5 = 1.1 \cdot \begin{cases} 7.4522 \cdot e^{0.2112 \cdot z} & z \le 2.69696 \\ 1.2033 \cdot e^{0.9595 \cdot z} & z > 2.69696 \end{cases} \qquad (10)$$

$$BOD_u = 1.5 \cdot BOD_5$$

Where: z = standard Gaussian random variable.

SRWTP Effluent Ammonia Concentrations

The SRWTP ammonia data are plotted in Figure 45 along with the monthly average values. The ammonia concentrations in the effluent change over time with water conservation additionally effluent ammonia concentrations were found to vary monthly. The annual average ammonia concentrations were used to normalize the measured SRWTP effluent concentrations to determine normalized monthly averages and corresponding normalized monthly variability. The normalized data and calculated distributions are presented in Figure 46. The ammonia concentrations normalized to an annual average, allows scenarios of differing effluent ammonia concentrations to be easily calculated by multiplying the normalized values by the desired ammonia levels.

As an example, the LDOPA calculated effluent ammonia concentrations from one recursion corresponding to an annual average of 10 mg/L as N are plotted in Figure 47. Additionally, the measured effluent ammonia concentrations scaled by their respective annual average to 10 mg/L as N are displayed on Figure 47 along with the LDOPA modeled scaled monthly average and 90% confidence interval. The distribution of LDOPA modeled SRWTP effluent daily ammonia concentrations scaled to an annual average of 10 mg/L as N is presented in Figure 48. Note a normal distribution fit data better than a log-normal distribution. Additionally, the distribution of SRWTP effluent monthly averaged ammonia concentrations is included on Figure 48. The distributions presented in Figure 48 are used to define the effluent limitations for ammonia. As with BOD_5, the sampling frequency for ammonia is such that the effluent limitations need to be based on percentiles reflective of the volume of data collected. Ammonia in the SRWTP effluent is sampled twice weekly, resulting in 520 daily samples and 60 monthly calculations in a permit cycle which correspond to the 99.808^{th} and 98.360^{th} percentiles, respectively.

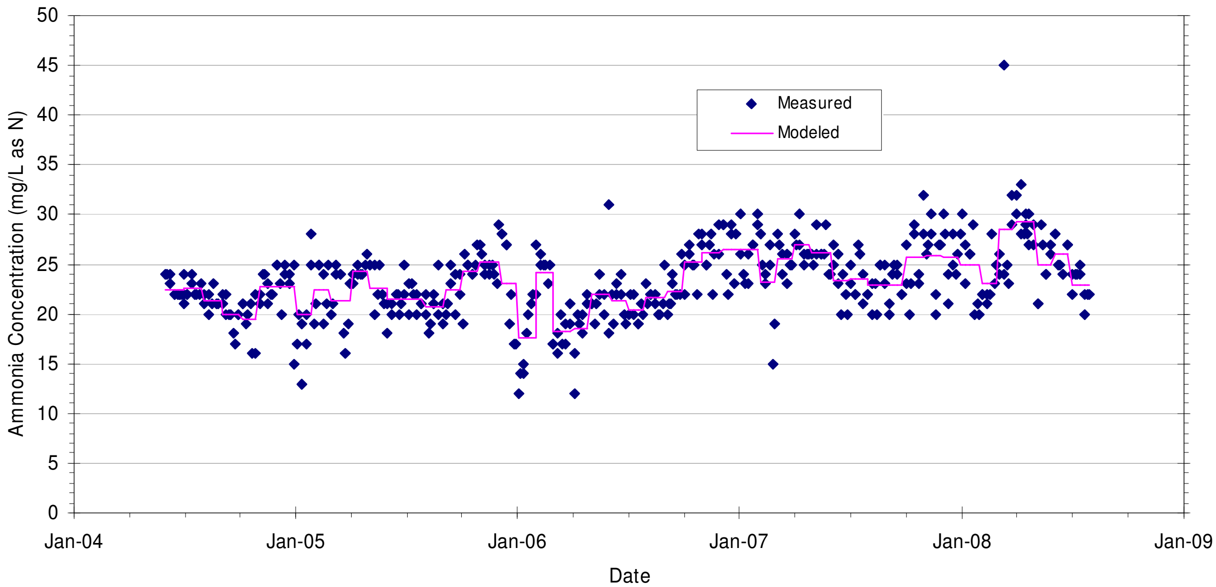


Figure 45: Time Series of Effluent Ammonia Concentrations Illustrating Increases in Concentrations with Increasing Water Conservation.

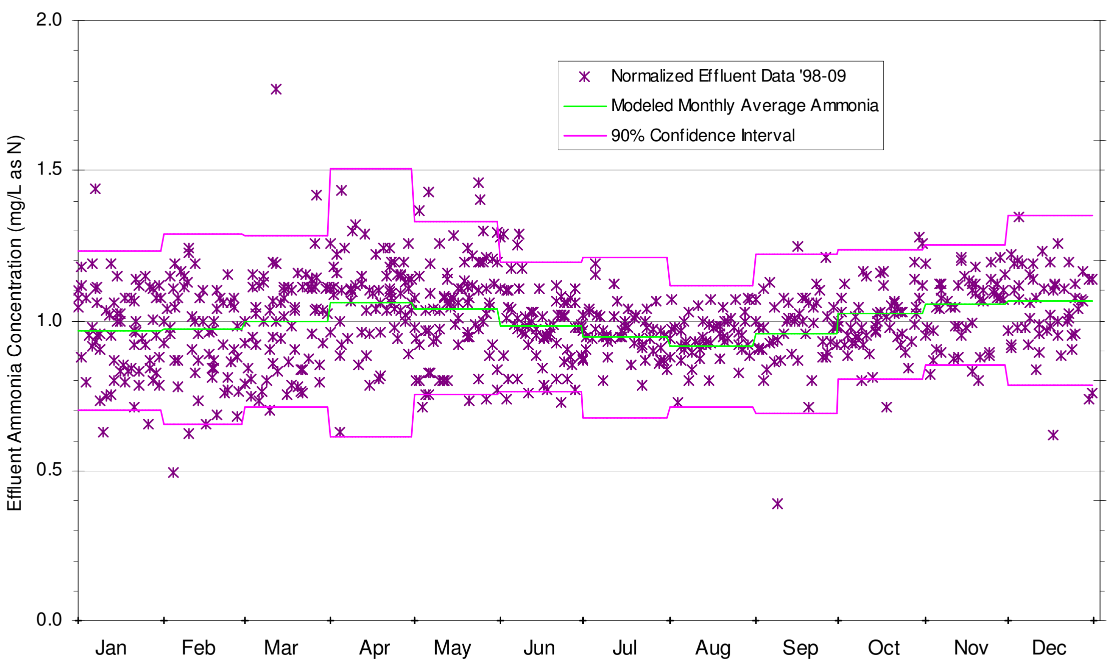


Figure 46: Normalized SRWTP Effluent Ammonia Concentrations with Monthly Distributions.

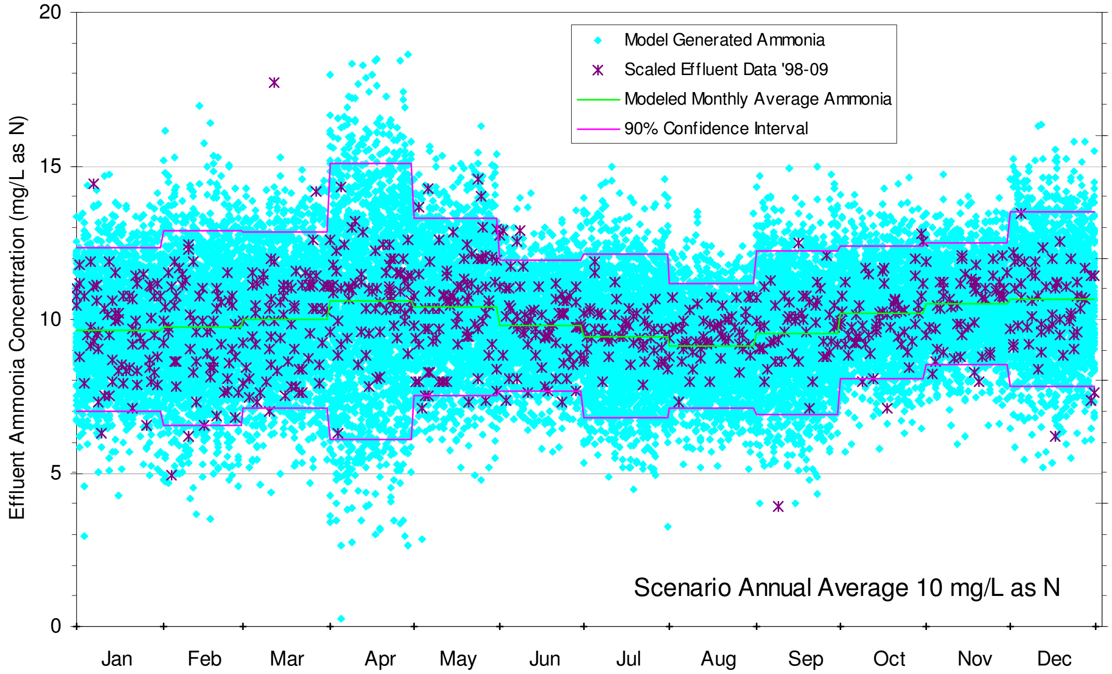


Figure 47: Effluent Ammonia Concentrations Scaled to an Annual Average of 10 mg/L as N. LDOPA calculated ammonia concentrations overlayed by scaled measured concentrations measured between June 2004 and March 2010.

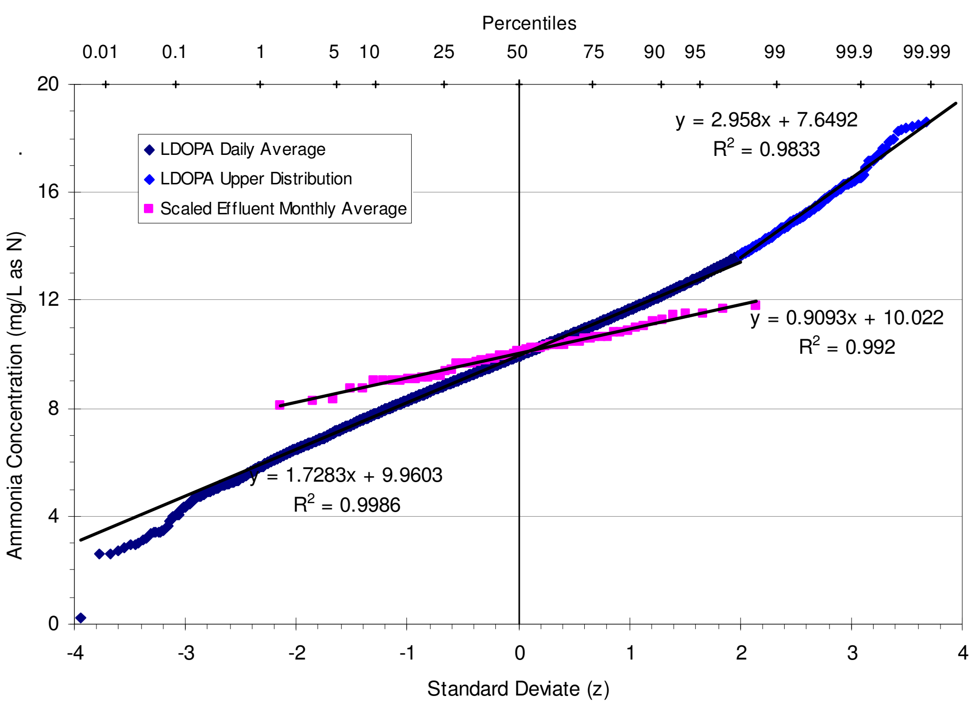


Figure 48: Distribution of SRWTP Effluent Ammonia. Daily Values from LDOPA Output, and Monthly Average Values from SRWTP Data from June 2004 through March 2010. Ammonia Concentrations Scaled to 10.0 mg/L as N.

SRWTP Effluent Organic Nitrogen Concentrations

Organic nitrogen is not measured in the SRWTP effluent, however both ammonia and total kheljah nitrogen (TKN) are measured. Organic nitrogen can be estimated in the SRWTP effluent by subtracting the ammonia concentration from the TKN concentration. However, the sample dates for ammonia and TKN do not generally correspond. To calculate the organic nitrogen the ammonia concentrations between sample dates were estimated by interpolating between data points. Estimates of the organic nitrogen in the effluent were calculated by subtracting the interpolated ammonia concentrations from the measured TKN values. In calculating the organic nitrogen concentrations, any value less than 0.5 mg/L as N was set to 0.5 mg/L as N. The time series of calculated organic nitrogen concentrations is presented in Figure 49. To investigate a potential relationship between ammonia concentrations and organic nitrogen concentration in the effluent, both constituents are plotted pair-wise in Figure 50, where it appears they are not correlated.

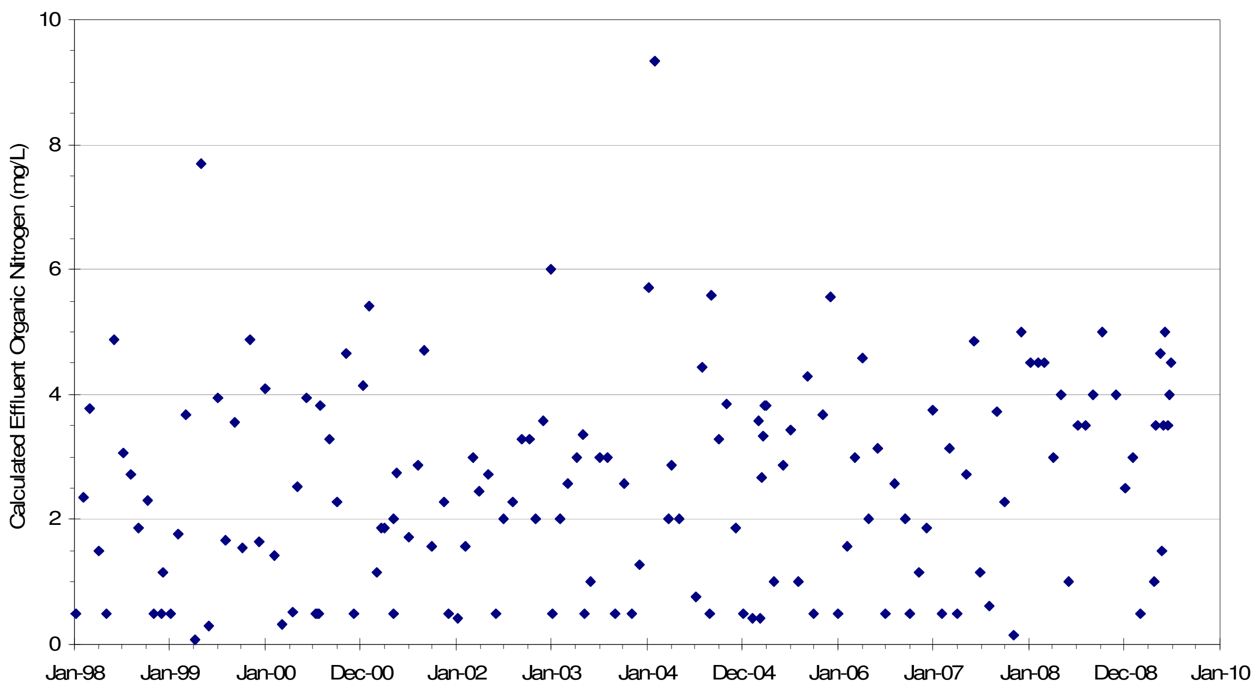


Figure 49: Time Series of Calculated Organic Nitrogen Concentrations in the SRWTP Effluent. (Organic Nitrogen = TKN - Ammonia).

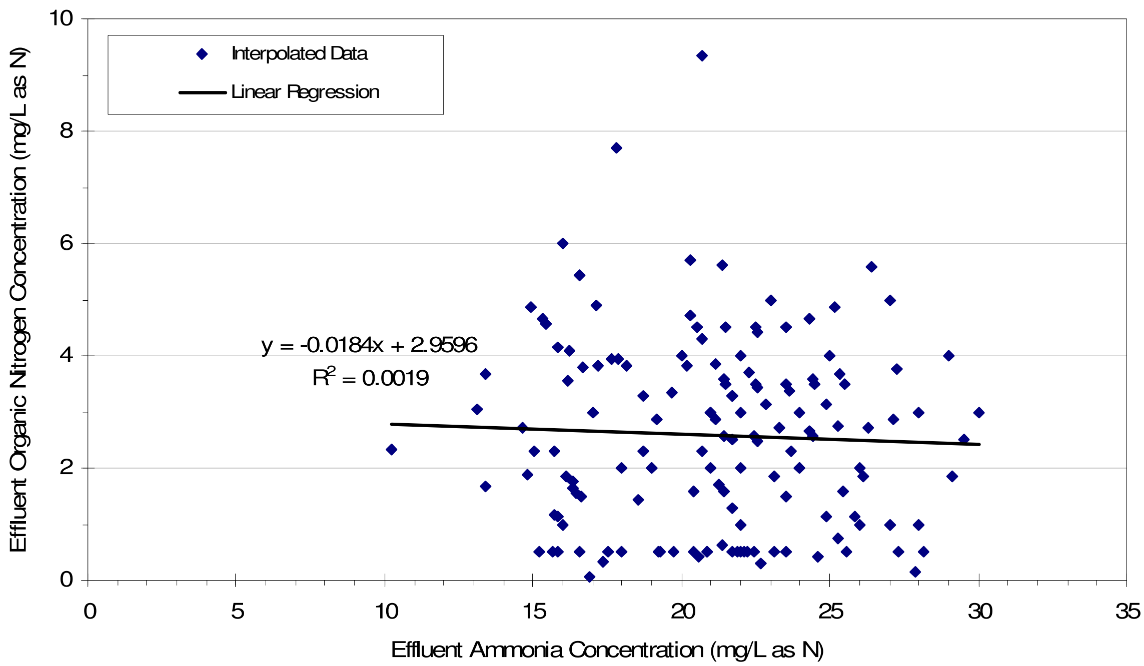


Figure 50: Relation Between Ammonia and Organic Nitrogen in the SRWTP Effluent.

DISCUSSION

Ammonia is a key variable for the calculation of downstream oxygen levels. The upstream measurements of ammonia are largely non-detect, and in the model the input ammonia is based on the averages based on one half the detection limits. To check the suitability of the input ammonia, measured ammonia at R-3 is compared to the modeled complete mixed ammonia concentrations. The river and effluent are not expected to be completely mixed by R-3 whereas the LDOPA model calculates the downstream concentrations assuming complete mix conditions, so the modeled results are not expected to exactly match measured values, however both measured and modeled results compare well. Additionally, the CMP data collected at RM44 are overlaid on the plot, note that as with R-3 the river is not expected to be completely mixed by RM44 under all conditions. The measured and modeled ammonia concentrations are presented in Figure 51.

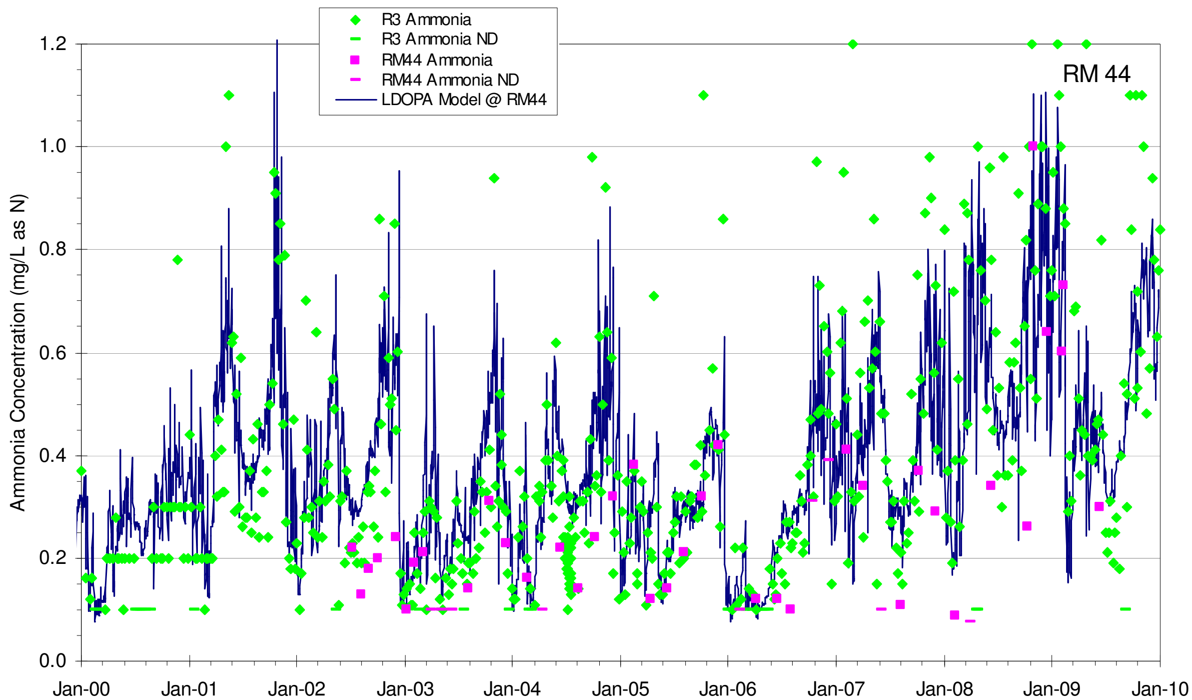


Figure 51: Measured Ammonia in Sacramento River at R-3 with Modeled Ammonia Downstream of the Discharge. The river and effluent are not necessarily completely mixed by R-3 or RM44, however the model assumes complete mix conditions.

The Streeter-Phelps model listed as Equation (19) is used to calculate the oxygen deficit downstream from the discharge. For the calendar year 2008, monthly average measured and modeled oxygen concentrations are presented in Figure 54.

Calibration

The model development specifies the values for nearly all the variables in the Streeter-Phelps equation. For the formulation of the Streeter-Phelps equation used in the model, only the dissolved oxygen consumption rates require calibration. During December 2008, continuous ammonia sensors were deployed in the Sacramento River at Freeport and at Hood. The time series of ammonia concentrations measured by the sensors is plotted in Figure 52. Superimposed on the ammonia concentrations is the continuous dissolved oxygen concentration measurements recorded by the DWR water quality station at Hood. During monitoring time-frame, there were 3 extended diversions of SRWTP effluent. On Figure 52 the diversion periods are marked by the sharp decrease in ammonia concentrations at Hood. The extended diversion periods occur where the ammonia concentration at Hood decreases and remains low for an extended period. The dissolved oxygen measured during the extended diversions increases by 0.6 to 0.8 mg/L as the ammonia levels fall to near background. In the timeframe when the extended diversions happened, the Sacramento River flow rate was 8,000 to 8,500 cfs and the water temperatures were 7 to 8 ºC. Using the river conditions in the model the consumptive rates can be calibrated to result in an approximate 0.6 to 0.8 mg/L drop in dissolved oxygen concentration.

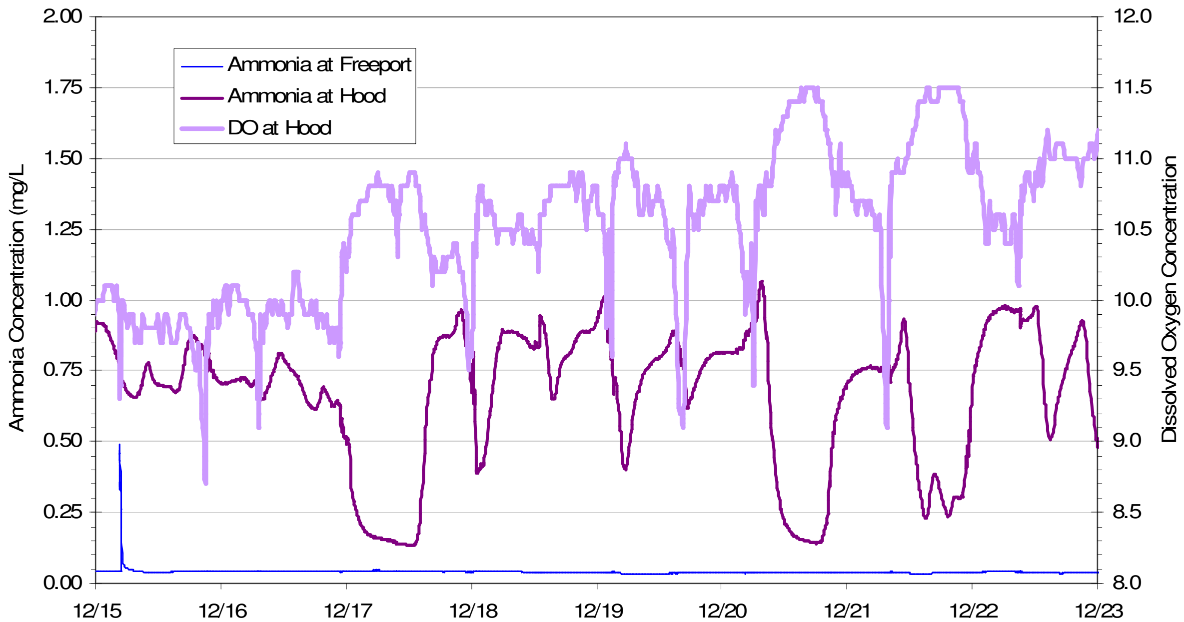


Figure 52: Continuous Sensor Data for Ammonia and Dissolved Oxygen Concentrations at Hood, December 2008.

A list of the calibrated values of reaction rates is included in Table 9. Additionally, rates considered for models of the nutrient cycle/dissolved oxygen cycle in the Delta are listed in the Table for comparison. Both Rajbhandari 1995 and RMA 2009 employ the DSM2-QUAL model to simulate the nutrient cycling in the Delta.

Table 9: LDOPA Model Temperature Coefficients and Rates for Modeled Parameters.

Parameter	Symbol	Temperature Coeff	LDOPA Rate (1/day)	Rajbhandari(2) Range (1/day)	RMA(3) Range (1/day)
Reaeration	k_2	1.024(1)	Equation (7) or (8)	Figure 27	Figure 27
Dissolved BOD	k_{dbod}	1.047(1)	0.11	0.02 – 3.4	0.12
Particulate BOD	k_{pbod}	1.058(1)	0.05	-0.36 – 0.36	0.1
Ammonia	k_{nh3}	1.080(1)	0.09	0.1 – 1.0	0.05 – 0.20
Organic Nitrogen	k_{orgN}	1.020(2)	0.02(2)	0.02 – 0.4	0.1

(1) U.S. EPA (1985)
(2) U.S. EPA (1990)
(3) Rajbhandari (1995)
(4) RMA (RMA 2009 DRAFT)

The continuous dissolved oxygen measurements at Hood and Rio Vista are the ideal data to calibrate the Streeter-Phelps model. The data maintained on the California data exchange (CDEC), is provisional and subject to revision. Continuous sensors may record noise, may contain drift, and potentially contain gaps. These types of corruptions impede detailed data analysis (Quilty, et al 2004). As an example of potential data corruption, the dissolved oxygen at

Hood is presented in Figure 53. Additionally, the saturation concentration based on the measured water temperature, and dissolved oxygen data collected at Freeport are superimposed on the figure. Note that the measured dissolved oxygen at Freeport follows the calculated saturation concentration. The dissolved oxygen recorded at Hood is considerably lower than the saturation concentration, and Hood is only approximately 8 miles from Freeport. In reviewing the data at Hood, in the reading immediately after February 1, 2008 at 10:00, the dissolved oxygen dropped 1.7 mg/L; and in the reading immediately after December 10, 2008 at 14:00, the dissolved oxygen increased by 1.5 mg/L. It appears that the dissolved oxygen at Hood read approximately 1.5 mg/L too low between February and December in 2008. The jump in dissolved oxygen was removed from the time series and plotted on Figure 53 as the adjusted dissolved oxygen at Hood. DWR is currently investigating the dissolved oxygen at hood and any corrections that may be necessary. The adjusted dissolved oxygen concentrations appear more realistic in terms of the Streeter-Phelps model, the observed upstream dissolved saturation concentrations, observed loads of oxygen demanding substances, and the typical rates the oxygen demanding substances are consumed. Note there still exists a large difference between the measured Freeport dissolved oxygen, which coincides with the calculated saturation concentration, and the dissolved oxygen readings from the continuous sensor at Hood during late October through December. These differences are too large to be explained by oxygen sag and are continued to be reviewed.

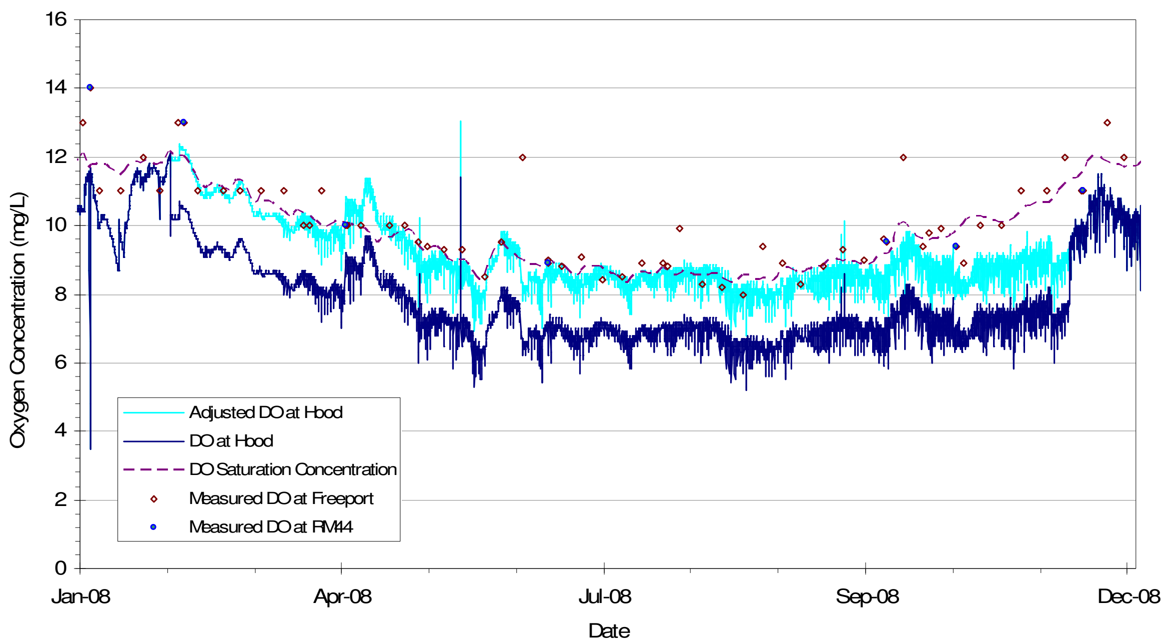
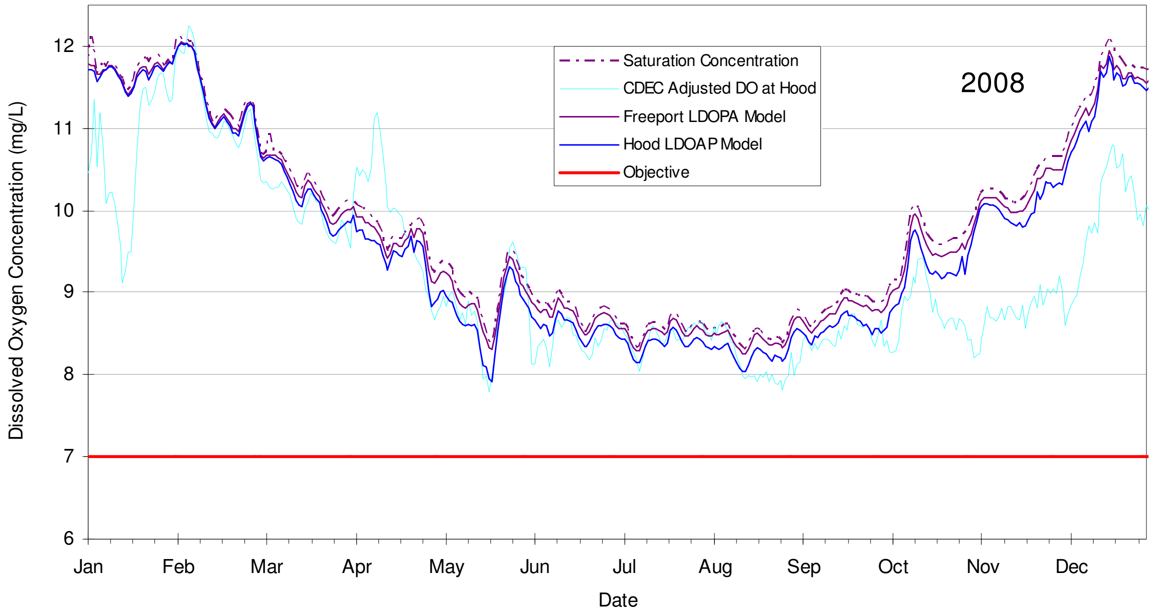


Figure 53: DWR Continuous Dissolved Oxygen Measurements at Hood.

The daily average adjusted dissolved oxygen concentration at Hood, and the daily average dissolved oxygen at Rio Vista are compared to the corresponding Streeter-Phelps calculated daily average dissolved oxygen concentrations in Figure 54. In calibrating the reaction rates, the match between measured and modeled dissolved oxygen in the May through September period was given the greatest weight.



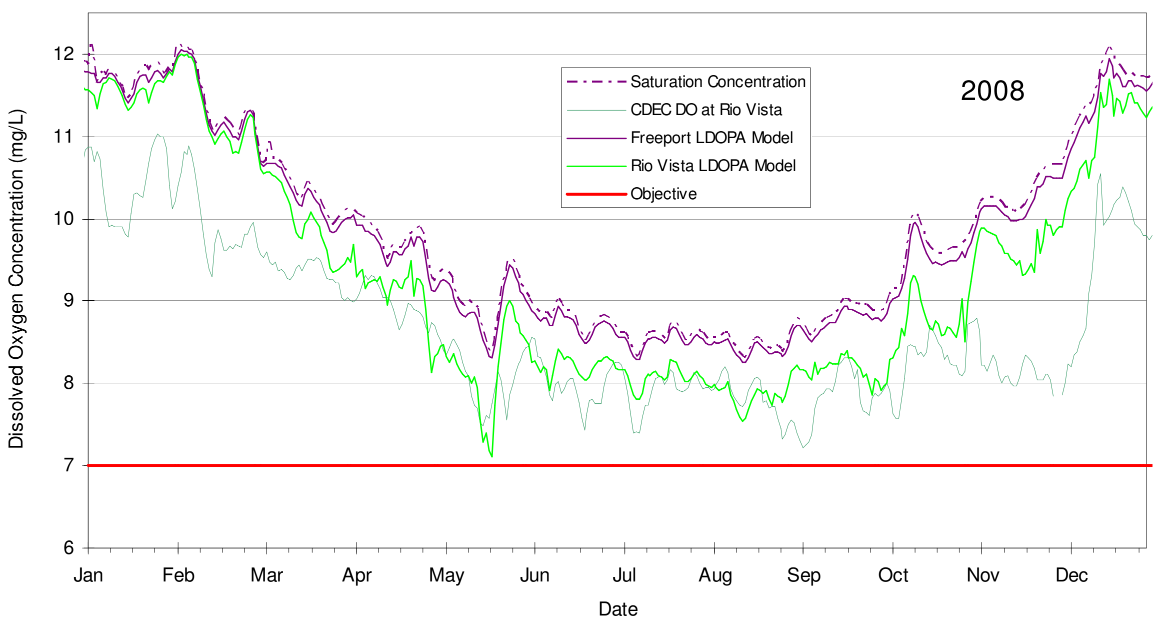


Figure 54: CDEC Measured and LDOPA Modeled Daily Average Dissolved Oxygen Concentrations at Freeport, Hood, and Rio Vista.

Validation

Using the calibrated LDOPA model, the recorded effluent flow rates and ammonia concentrations were used to simulate the period January 1985 to December 2009. Freeport 15-minute flow data from USGS were used as the basis to develop the hourly flows used for validation run input. USGS 15-minute data are available from 1989 to the present. Hourly flow rate data from the CDEC station at Freeport were used to fill in the missing timeframes of the USGS data set. Additionally, where data were missing from both USGS and CDEC data sets, flow values from portions of existing record with similar daily average flow rates were used to fill gaps. The complied data set is displayed in Figure 55, with the USGS data shown as a solid line with individual hours of filled in data shown as overlaid dots.

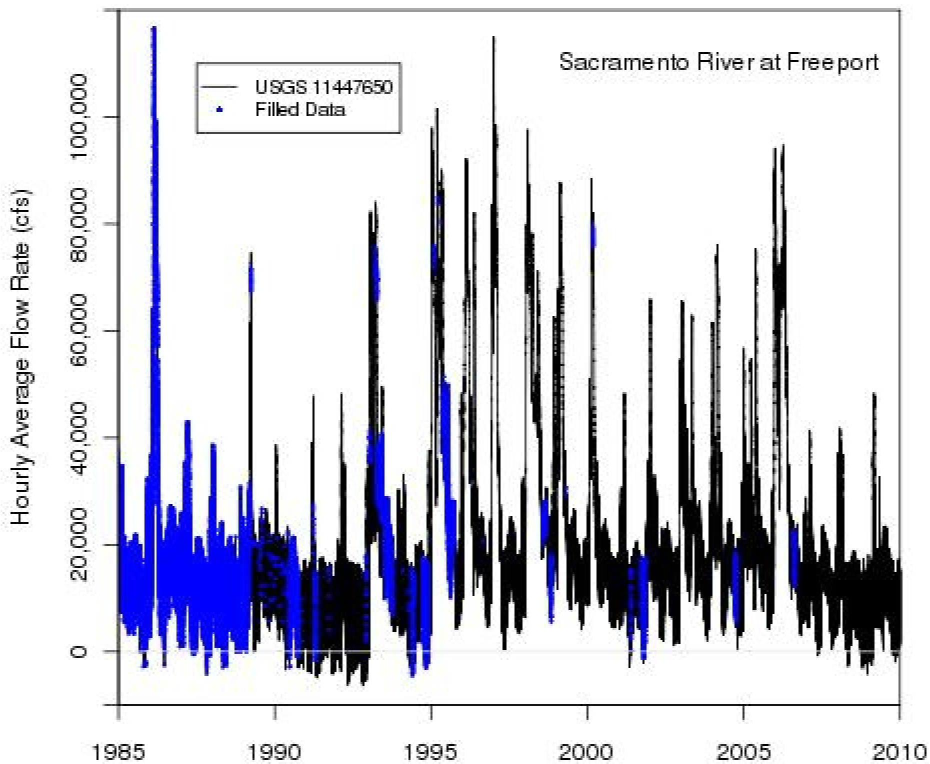


Figure 55: Hourly Flow Rate Data for the Sacramento River at Freeport Compiled from USGS (Station 11447650) 15-minute and CDEC (Station FTP) 1-hour data.

The input Sacramento River temperature data set spanning 1985 – 2010 was developed based on the continuous data recorded at Hood by DWR (CDEC station SRH). The DWR data set spans December 28, 1998 through current day. The data from water years with matching water year type as defined by the Sacramento River Indices were used to extend the data set from 1985 to 2010. The compiled data set for temperature used in the validations runs is presented in Figure 56 and is compared to the available receiving water monitoring data. Measured temperature at Freeport from the USGS and SRCSD are overlaid on the modeled temperature.

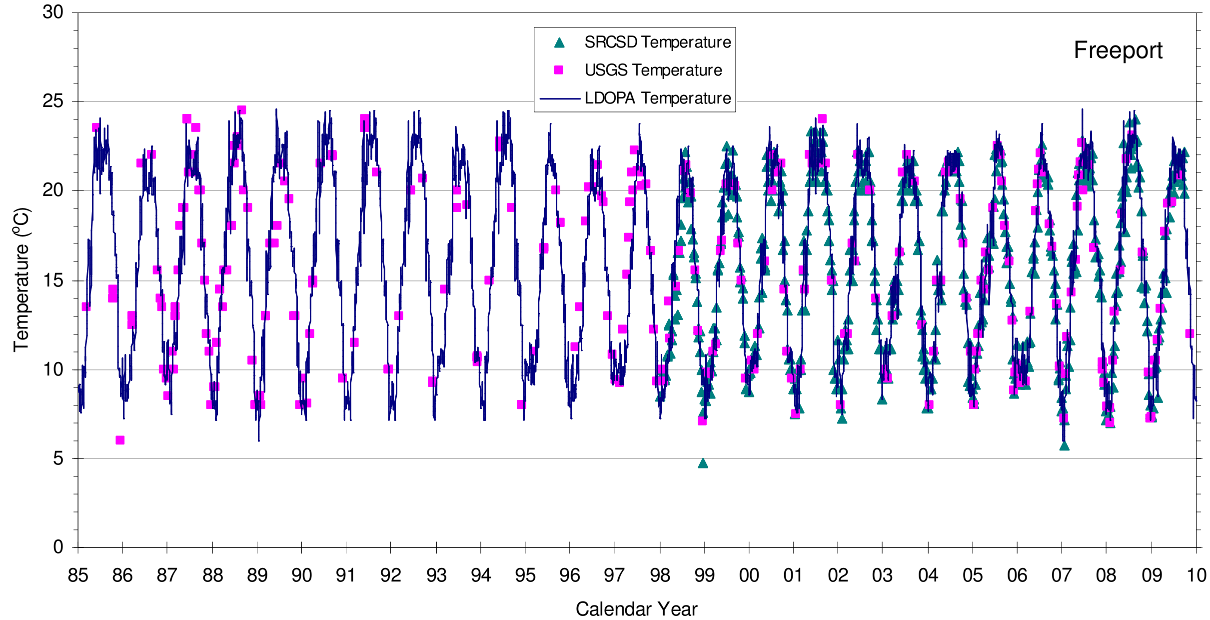


Figure 56: Freeport Temperature Input Data used in Validation Runs Compared to Available Receiving Water Monitoring Data at Freeport.

Downstream ammonia concentrations resulting from the validation run are compared to the municipal water quality investigation data for ammonia at Hood Station 3A in Figure 57.

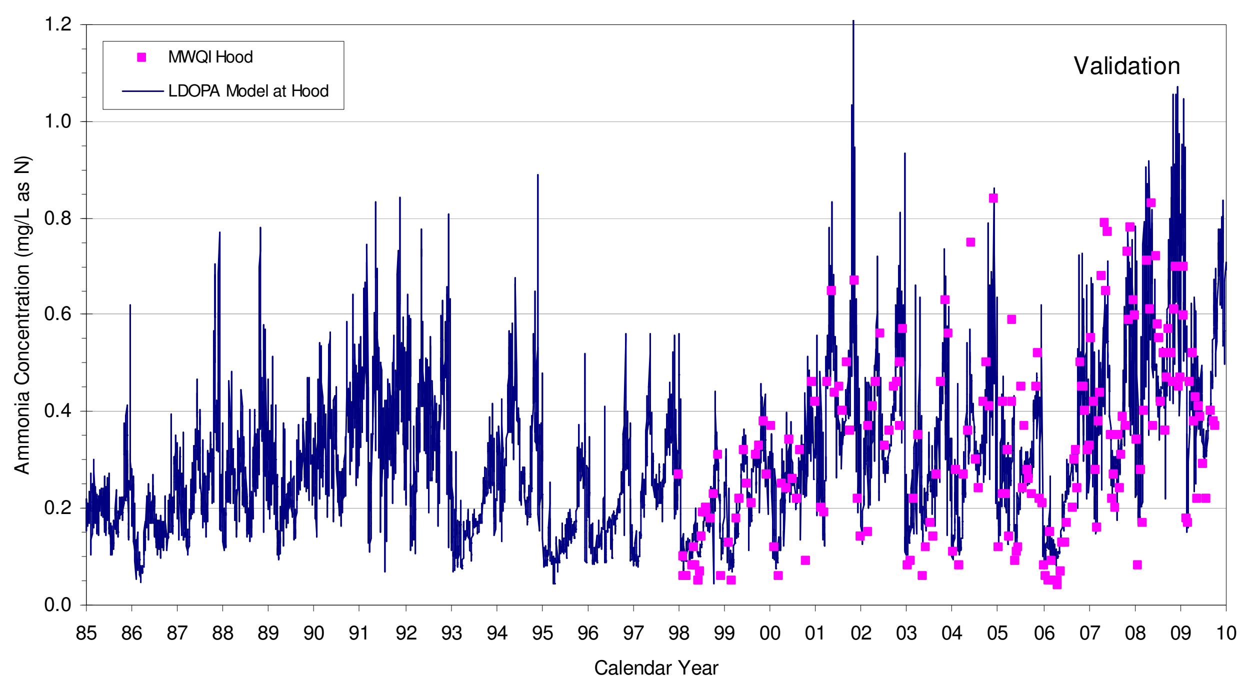


Figure 57: Comparison of LDOPA Modeled and MWQI Measured Ammonia Concentrations in the Sacramento River at Hood.

The model simulation at Rio Vista is compared to the measured values at Rio Vista. During the May to September period, the model matches the measurements well. Differences in the October to April time-frame are partially due to disaggregating the monthly average flow rates from PROSIM into hourly values, and partially due to changes in operations and demand that moves water through the system differently than in the 80's. Additionally, the monitoring data reveal that the dissolved oxygen concentrations at Emmaton are typically greater than the concentrations at Rio Vista, meaning the increased channel width and available wind induced reaeration result in Rio Vista being the critical location in terms of dissolved oxygen sag. Downstream dissolved oxygen concentrations calculated by the LDOPA model are compared to data from the environmental monitoring program (EMP) and USGS where available in Figures Figure 58 through Figure 60 for the Sacramento River at Rio Vista, Emmaton, and the confluence with the San Joaquin River, respectively.

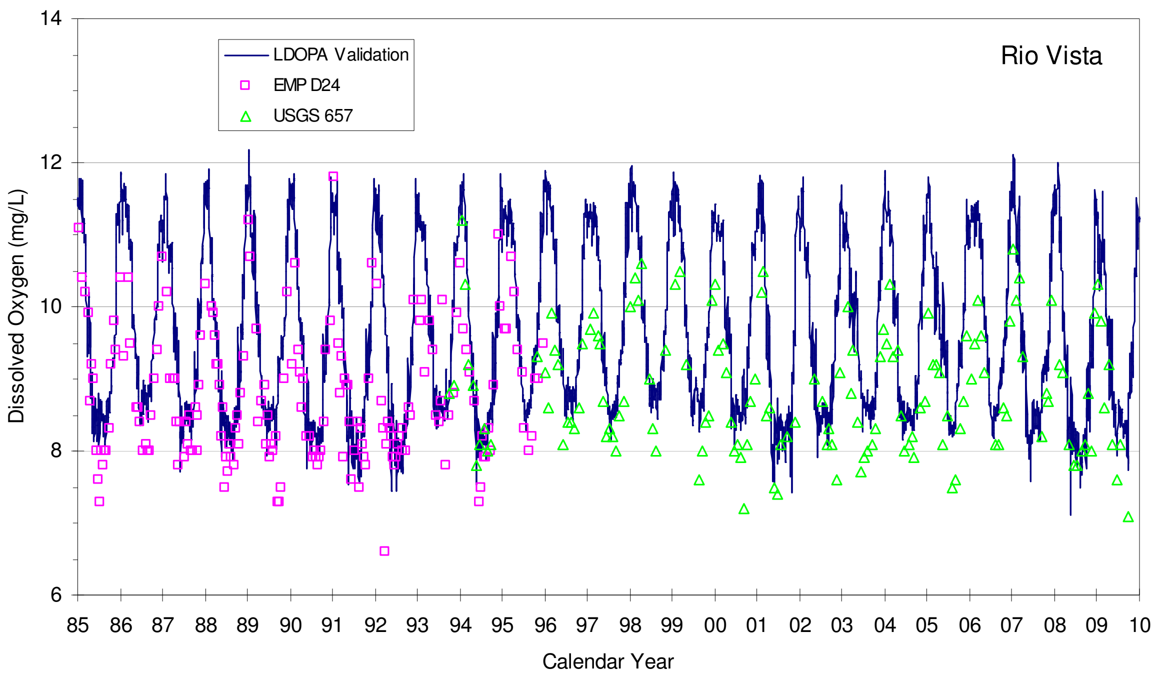


Figure 58: Validation Run of LDOPA Model with Measured Dissolved Oxygen Data for the Sacramento River at Rio Vista (RM 13).

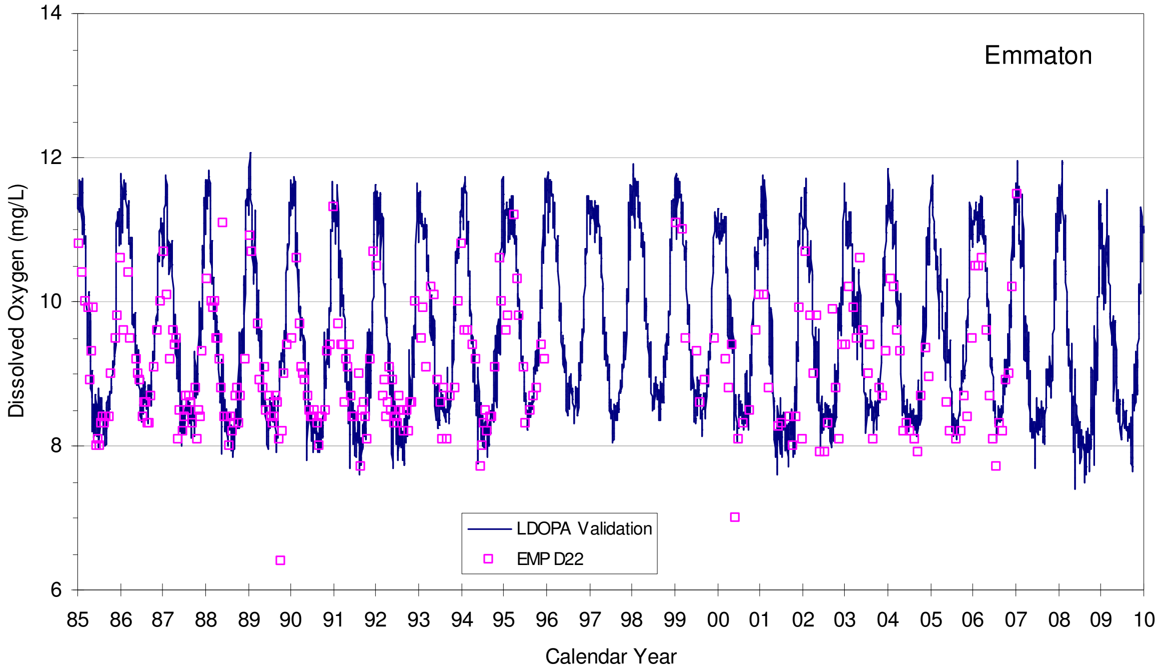


Figure 59: Validation Run of LDOPA Model with Measured Dissolved Oxygen Data for the Sacramento River at Emmaton (RM 7)

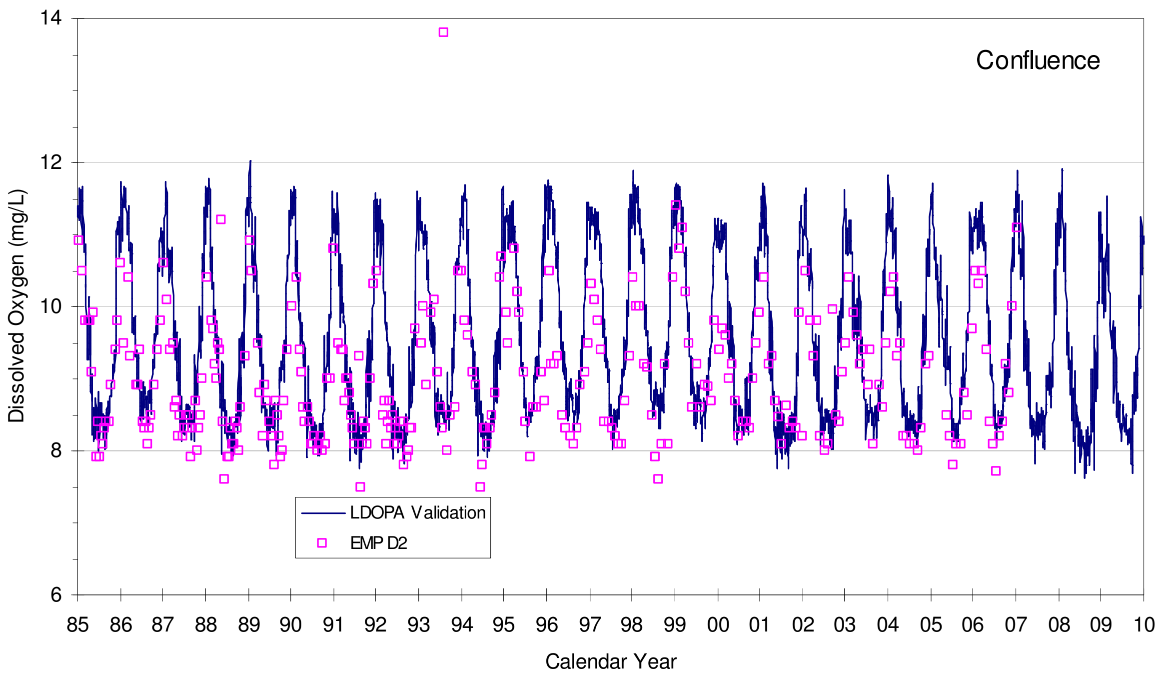


Figure 60: Validation Run of LDOPA Model with Measured Dissolved Oxygen Data for the Confluence of the Sacramento and San Joaquin Rivers (RM 0).

RESULTS

The 70-year period of record run through the calibrated and validated Streeter-Phelps model for an effluent flow rate of 218 MGD and effluent ultimate oxygen demanding load[15] so that the minimum downstream dissolved concentration is at least 7.0 mg/L with 95% confidence, results in the dissolved oxygen time series plotted in Figure 61. Note that the 218 mgd scenario maintains current ultimate oxygen concentrations November through April and reduces effluent ultimate oxygen demanding substances May through October. Additionally, the time series of daily average river flow rates is included on the figure. Note that for the scenario, none of the calculated daily dissolved oxygen values was at or below 7.0 mg/L. The dissolved oxygen is plotted as a function of the paired daily average river flow rate in Figure 62. The dissolved oxygen plotted as a function of the paired daily average river temperature are plotted in Figure 63.

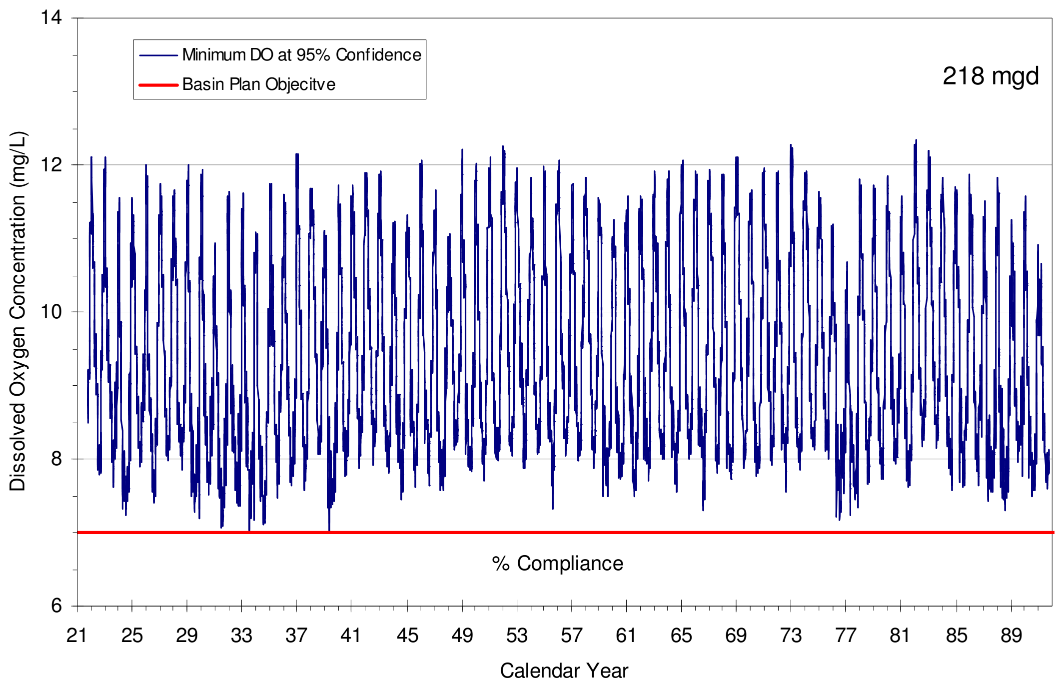


Figure 61: Time Series of Modeled Dissolved Oxygen In the Sacramento River downstream of Freeport and Sacramento River Daily Average Flow rates.

[15] $UOD = 8.34 \cdot [1.5 \cdot BOD_5 + 4.6 \cdot Ammonia] \cdot Q_{eff}$ with BOD_5 in mg/L, ammonia in mg/L as N, and Q_{eff} in mgd.

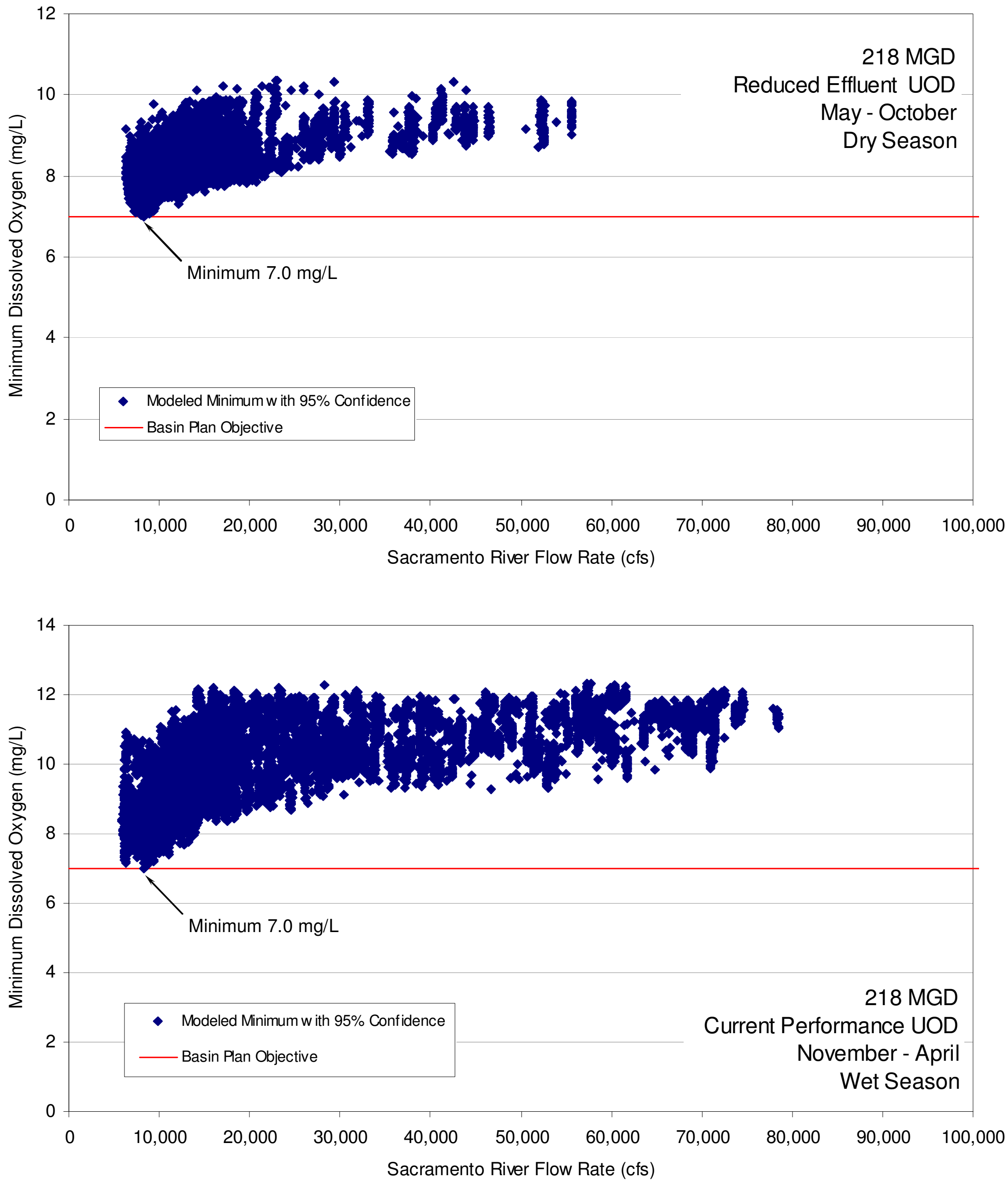
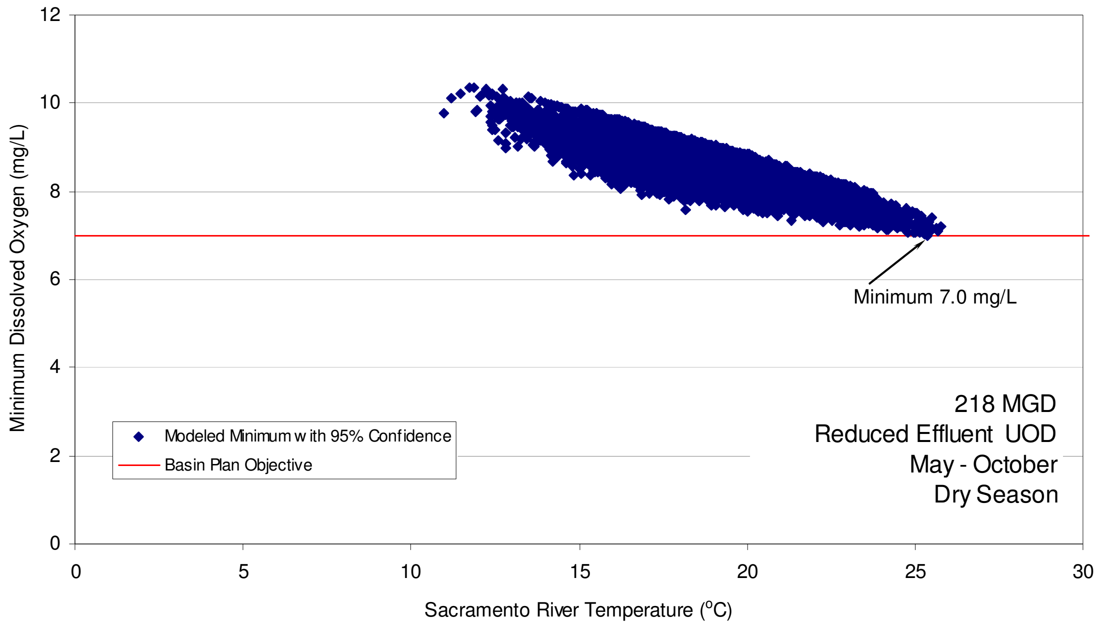


Figure 62: Paired Daily Average River Flow rate and Modeled Dissolved Oxygen in the Sacramento River Downstream of Freeport for 218 MGD Effluent Flow rate



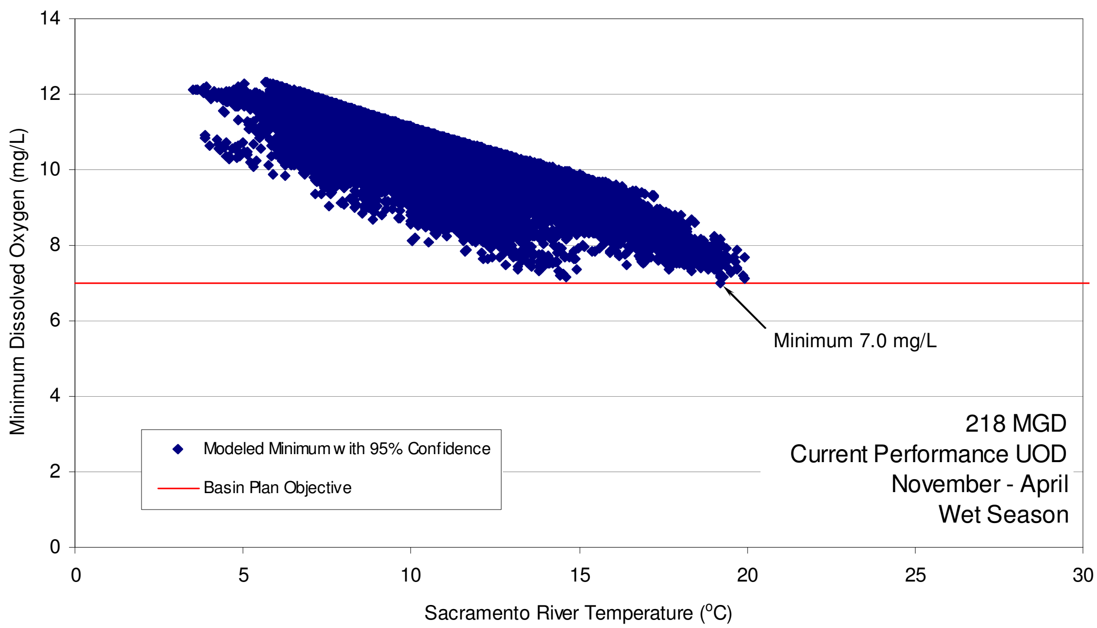


Figure 63: Paired Daily Average Water Temperature and Modeled Dissolved Oxygen in the Sacramento River for 218 MGD Effluent Flow rate .

CONCLUSIONS

Conservative assumptions for the model include:

SRWTP Effluent dissolved oxygen concentration set to 2.0 mg/L

Ammonia is not modeled to volatilize or otherwise be removed from the system except by nitrification.

Wind effects are not included between Freeport and Isleton.

The Streeter-Phelps model was validated.

The LDOPA model is conservative, because the river flow conditions are held constant for the entire flow duration through the model domain. Critical low flow rate high temperature conditions do not typically persist for multiple consecutive days.

The continuous dissolved oxygen data available from DWR via CDEC is being reviewed and should not be treated as final data until such time as the review is completed.

River and effluent flow rates, temperature, and ammonia concentrations have the greatest affect on downstream dissolved oxygen concentrations.

Historic dissolved oxygen measurements at Rio Vista and downstream at Emmaton and Chipps Island reveal that, generally, Rio Vista represents the critical point of low dissolved oxygen. Downstream of Rio Vista, the river channel widens considerably allowing greater wind induced reaeration and the ship channel and sloughs add flows to the main channel flows. The developed model is not valid downstream of Rio Vista.

REFERENCES

Covar A.P. (1976), Selecting the Proper Reaeration Coefficient for use in Water Quality Models, Proceeding of the U.S. EPA Conference on Environmental Simulation and Modeling, Cincinnati, Ohio

Sacramento Regional County Sanitation District (SRCSD 2009), "Administrative Draft Antidegredataion Analysis for Proposed Discharge Modification for the Sacramento Regional Wastewater Treatment Plant", May 20, 2009, prepared by Larry Walker Associates.

Rajbhandari, H. (1995) California Department of Water Resources: 1995 Annual Progress Report, Chap 3: Water Quality.

Resource Management Associates (RMA 2008) "Modeling the Fate and Transport of Ammonia using DSM2-QUAL - DRAFT", October 2009.

Tchobanoglous and Schroeder (1985), *Water Quality*, Addison-Wesley Publishing Company, Inc., Reading, MA.

USEPA (1976), Quality Criteria for Water (the Red Book), Stock No. 055-001-01049-4, July 1976.

USEPA (1985), *Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling, Second Ed.*, EPA/600/3-85/040, June 1985.

USEPA (1986), Ambient Water Quality Criteria for Dissolved Oxygen, EPA 440/5-86-003, April 1986.

USEPA (1990), Technical Guidance Manual for Performing Waste Load Allocations; Book III Estuaries; Part 2 Application of Estuarine Waste Load Allocation Models, EPA , May 1990.

Page intentionally blank

APPENDIX B: DERIVATION OF MULTIPLE CONSTITUENT STREETER-PHELPS EQUATION

The dissolved oxygen in a flowing water body may be analyzed using the Streeter-Phelps equation (Tchobanoglous and Schroeder, 1985), listed as Equation (11).

$$D_{O_2} = \frac{kL_i}{k_2 - k}\left(e^{-k\Theta_H} - e^{-k_2\Theta_H}\right) + D_i e^{-k_2\Theta_H} \tag{11}$$

Where:

D_{O_2} = Oxygen deficit, saturation concentration – water column concentration, at a flow time Θ_H from the point of discharge (mg/L)

D_i = Initial oxygen deficit at the point of discharge (mg/L)

Θ_H = Hydraulic flow time (d)

L_i = Initial concentration of the total oxygen demanding substances expressed as ultimate oxygen demand (mg/L)

k = Total effective degradation rate for oxygen demanding substances (1/d)

k_2 = Oxygen reaeration rate (1/d)

To assess the oxygen sag due to a discharge using Equation (11), the equivalent ultimate oxygen demand for all carbonaceous, particulate, and nitrogen components present in the water column need to be combined into the one lumped parameter. The derivation of the new equation follows the general procedure in Tchobanoglous and Schroeder (1985). A new equation is necessary to independently evaluate carbonaceous, particulate, and nitrogen oxygen demanding substances which begins with a mass balance for oxygen through a control volume, ΔV. Oxygen is consumed from the modeled control volume by degradation of the oxygen demanding constituents at a first order rate. Oxygen in the control volume is replenished based on the difference between the saturation concentration and water column concentration of oxygen and a mass transfer rate modeled as a first order rate. Inserting the parameters of interest into the mass balance equation for an infinitesimal volume ΔV of width Δx, yields Equation (12).

$$\textit{Accumulation} = \text{In - Out + Generation}$$

$$\frac{\partial C_{O_2}}{\partial t}\Delta V = Q \cdot C_{O_2}\Big|_x - Q \cdot C_{O_2}\Big|_{x+\Delta x} + \Delta V \cdot \left[-k_{db}L_{db} - k_{pb}L_{pb} - k_{nh_3}L_{nh_3} + k_2 \cdot \left(C_{sat} - C_{O_2}\right)\right] \tag{12}$$

To yield a discretely solvable equation, Equation (12) is made steady state by setting $\frac{\partial C_{O_2}}{\partial t} = 0$. Equation (12) is divided by the size of the control volume, ΔV, and the control volume is made infinitely small; so that the in – out terms become: $\frac{Q \cdot C_{O_2}\big|_x - Q \cdot C_{O_2}\big|_{x+\Delta x}}{\Delta V} = Q \cdot \frac{\partial C_{O_2}}{\partial V}$. The equation is than "normalized" for flow and channel geometry into time by using the hydraulic flow time: $Q \cdot \frac{\partial C_{O_2}}{\partial V} = \frac{\partial C_{O_2}}{\partial \Theta_H}$. By swapping the dissolved oxygen concentration for the oxygen deficit and noting that an increase in dissolved oxygen is a decrease in deficit the following substitutions may be made: $\frac{\partial C_{O_2}}{\partial \Theta_H} = -\frac{\partial D_{O_2}}{\partial \Theta_H}$, where $D_{O_2} = \left(C_{sat} - C_{O_2}\right)$. With the modifications, Equation (12) becomes a differential equation for the oxygen deficit as listed in Equation (13).

$$-\frac{\partial D_{O_2}}{\partial \Theta_H} = -k_{db}L_{db} - k_{pb}L_{pb} - k_{nh_3}L_{nh_3} + k_2 D_{O_2} \tag{13}$$

Where:

k_{db} = dissolved BOD first order degradation rate (1/day)

L_{db} = ultimate oxygen demand from dissolved BOD (mg/L)

k_{pb} = particulate BOD first order degradation rate (1/day)

L_{pb} = ultimate oxygen demand from particulate BOD (mg/L)

k_{nh3} = first order nitrification rate (1/day)

L_{nh3} = ultimate oxygen demand from nitrification (mg/L)

Degradation of the oxygen demanding constituents is modeled as first-order degradation from the point of discharge. The dissolved carbonaceous oxygen demand in terms of the hydraulic float time from the point of discharge is listed in Equation (14):

$$L_{db} = L_{db_i} e^{-k_{db}\Theta_H} \tag{14}$$

Where L_{dbi} = ultimate oxygen demand of dissolved BOD at the point of discharge.

The particulate carbonaceous oxygen demanding substances are allowed to be degraded (k_{pd}) and settled (k_s) from the water column for an effective first-order degradation rate of $k_r = k_{pb} + k_s$, to yield Equation (15) as a function of hydraulic float time fro the point of discharge. Generally, the settling rate can be approximated by dividing the settling velocity (v_s) of the particles by the water depth (D), $k_s = {}^{v_s}\!/_{D}$ (USEPA 1990).

$$L_{pb} = L_{pb_i} e^{-k_r\Theta_H} \tag{15}$$

Where:

L_{pbi} = ultimate oxygen demand of particulate BOD at the point of discharge.

The nitrogen oxygen demand in terms of the hydraulic flow time may be written as Equation (16) in terms of the hydraulic float time from the point of discharge. The details of the nitrogen oxygen demand derivation are discussed below, and is Equation (23) multiplied by the oxygen consumed per ammonia degraded.

$$L_{nh_3} = L_{nh_{3i}} e^{-k_{nh3}\Theta_H} + \frac{O_2}{N} \frac{k_{OrgN} \cdot OrgN_i \cdot}{\left(k_{nh_3} - k_{OrgN}\right)} \left(e^{-k_{OrgN}\Theta_H} - e^{-k_{nh3}\Theta_H}\right) \tag{16}$$

Where:

L_{nh3i} = ultimate oxygen demand of ammonia nitrification at the point of discharge (mg/L).

k_{OrgN} = first order ammonification rate of organic nitrogen to ammonia (1/day).

OrgNi = initial organic nitrogen concentration at the point of discharge (mg/L as N)

O_2/N = stoichiometric ratio of oxygen consumed per nitrification.

Collecting all the deficit variables to the left hand side and treating each of the oxygen demanding substances as first order degradation from the point of discharge results in Equation (17). Note the nitrogen oxygen demand is rearranged for convenience.

$$\frac{\partial D_{O_2}}{\partial \Theta_H} + k_2 D_{O_2} = k_{db} L_{db_i} e^{-k_{db}\Theta_H} + k_{pb} L_{pb_i} e^{-k_r \Theta_H} + \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})} e^{-k_{OrgN}\Theta_H} + \left(k_{nh_3} L_{nh_{3i}} - \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})} \right) e^{-k_{nh_3}\Theta_H} \tag{17}$$

Using an integrating factor of $e^{k_2\Theta_H}$, allows Equation (17) to be integrated.

$$e^{k_2\Theta_H} \frac{\partial D_{O_2}}{\partial \Theta_H} + k_2 e^{k_2\Theta_H} D_{O_2} = k_{db} L_{db_i} e^{k_2\Theta_H} e^{-k_{db}\Theta_H} + k_{pb} L_{pb_i} e^{k_2\Theta_H} e^{-k_r \Theta_H} + \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})} e^{k_2\Theta_H} e^{-k_{OrgN}\Theta_H} + \left(k_{nh_3} L_{nh_{3i}} - \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})} \right) e^{k_2\Theta_H} e^{-k_{nh_3}\Theta_H}$$

$$\frac{\partial e^{k_2\Theta_H} D_{O_2}}{\partial \Theta_H} = k_{db} L_{db_i} e^{(k_2 - k_{db})\Theta_H} + k_{pb} L_{pb_i} e^{(k_2 - k_r)\Theta_H} + \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})} e^{(k_2 - k_{OrgN})\Theta_H} + \left(k_{nh_3} L_{nh_{3i}} - \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})} \right) e^{(k_2 - k_{nh_3})\Theta_H}$$

Integrating and dividing through by the integrating factor results in Equation (18).

$$D_{O_2} = \frac{k_{db} L_{db_i}}{k_2 - k_{db}} e^{-k_{db}\Theta_H} + \frac{k_{pb} L_{pb_i}}{k_2 - k_r} e^{-k_r\Theta_H} + \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})(k_2 - k_{OrgN})} e^{-k_{OrgN}\Theta_H} + \left(\frac{k_{nh_3} L_{nh_{3i}}}{(k_2 - k_{nh_3})} - \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})(k_2 - k_{nh_3})} \right) e^{-k_{nh_3}\Theta_H} + K e^{-k_2\Theta_H} \tag{18}$$

At the point of discharge the flow time is zero and there is an initial deficit (D_i), allowing the integration constant to be determined:

$$D_i = \frac{k_{db} L_{db_i}}{k_2 - k_{db}} + \frac{k_{pb} L_{pb_i}}{k_2 - k_r} + \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})(k_2 - k_{OrgN})} + \left(\frac{k_{nh_3} L_{nh_{3i}}}{(k_2 - k_{nh_3})} - \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})(k_2 - k_{nh_3})} \right) + K$$

Substituting the integration constant into Equation (18), yields the oxygen deficit equation with dissolved and particulate carbonaceous oxygen demand, and nitrogenous oxygen demand exerted by nitrification of ammonia considering the ammonification of organic nitrogen is presented as Equation (19).

$$D_{O_2} = \frac{k_{db} L_{db_i}}{k_2 - k_{db}} \left(e^{-k_{db}\Theta_H} - e^{-k_2\Theta_H} \right) + \frac{k_{pb} L_{pb_i}}{k_2 - k_r} \left(e^{-k_r\Theta_H} - e^{-k_2\Theta_H} \right) + \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})(k_2 - k_{OrgN})} \left(e^{-k_{OrgN}\Theta_H} - e^{-k_2\Theta_H} \right) + \left(\frac{k_{nh_3} L_{nh_{3i}}}{(k_2 - k_{nh_3})} - \frac{O_2}{N} \frac{k_{nh_3} k_{OrgN} \cdot OrgN_i \cdot}{(k_{nh_3} - k_{OrgN})(k_2 - k_{nh_3})} \right) \left(e^{-knh_3\Theta_H} - e^{-k_2\Theta_H} \right) + D_i e^{-k_2\Theta_H} \tag{19}$$

Derivation of the Nitrogen Oxygen Demand

To incorporate both ammonia and organic nitrogen in the nitrogen oxygen demand, a relationship must be determined to account for the ammonification of organic nitrogen. Organic nitrogen does not exert an oxygen demand per se, but is incorporated into cell material and released as ammonia on decay of the cell material (USEPA, 1990). Derivation of the model directly incorporates the ammonification of organic nitrogen, effectively increasing the ammonia concentration in the water column which then may exert an oxygen demand. Ammonia and organic nitrogen are linked via two coupled mass balance equations as presented in Equation (20). The concentration of ammonia is reduced by a first order consumption and increased by the first order ammonification of organic nitrogen. Organic nitrogen is modeled to transform to ammonia at a first order rate.

$$\begin{aligned}
\frac{\partial NH3}{\partial t}\Delta V &= Q\cdot NH3\big|_{x} - Q\cdot NH3\big|_{x+\Delta x} + \Delta V\cdot\left[-k_{nh_3}NH3 + k_{OrgN}OrgN\right] \\
\frac{\partial OrgN}{\partial t}\Delta V &= Q\cdot OrgN\big|_{x} - Q\cdot OrgN\big|_{x+\Delta x} + \Delta V\cdot\left[-k_{OrgN}OrgN\right]
\end{aligned} \tag{20}$$

Under steady state conditions and in terms of the hydraulic flow time, the mass balance equations become:

$$\begin{aligned}
\frac{\partial NH3}{\partial \Theta_H} &= -k_{nh_3}NH3 + k_{OrgN}OrgN \\
\frac{\partial OrgN}{\partial \Theta_H} &= -k_{OrgN}OrgN
\end{aligned}$$

The equation for organic nitrogen may be integrated directly to yield Equation (21).

$$OrgN = OrgN_i e^{-k_{OrgN}\Theta_H} \tag{21}$$

Substituting Equation (21) into the ammonia mass balance equation results in Equation (22), which is exactly the same form as the classic Streeter-Phelps equation and is solved similarly with an integrating factor of $e^{k_{nh3}\Theta_H}$.

$$\frac{\partial NH3}{\partial \Theta_H} = -k_{nh_3}NH3 + k_{OrgN}\cdot OrgN_i e^{-k_{OrgN}\Theta_H} \tag{22}$$

Solving Equation (22) leads to an equation accounting for the first order degradation of ammonia originally present plus the amount of ammonia produced from ammonification less the amount degraded at a first order rate, listed as Equation (23). The nitrogen oxygen demand is determined by multiplying Equation (23) through by the ratio of oxygen consumed per ammonia degraded.

$$NH3 = NH3_i e^{-k_{nh3}\Theta_H} + \frac{k_{OrgN}\cdot OrgN_i\cdot}{\left(k_{nh_3} - k_{OrgN}\right)}\left(e^{-k_{OrgN}\Theta_H} - e^{-k_{nh3}\Theta_H}\right) \tag{23}$$